# Spatial processes in linear ordering

Ulrich von Hecker[1], Karl Christoph Klauer[2],

Lukas Wolf[1] and Masoud Fazilat-Pour[3]

[1]School of Psychology, Cardiff University, UK.

[2]Albert-Ludwigs-Universität, Freiburg, Germany.

[3]Shahid Bahonar University of Kerman, Iran.

**Author Note**

**Correspondence should be addressed to Ulrich von Hecker, School of Psychology, Cardiff University, Tower Building, Park Place, Cardiff, CF10 3AT, United Kingdom. Electronic mail may be sent to vonheckeru@cardiff.ac.uk.**

**We would like to thank Muhammad-Raoof AnjomShoa, Natalie Felida, Laura Guthof, Ellen Hill, Dr. Rainer Leonhart, Emma McEwen, Shrabani Naha and Kathleen Trychta for help with data collection, as well as Craig Leth-Steensen, Michael Waldmann, and two anonymous reviewers for helpful comments on an earlier version.**

## Abstract

Memory performance in linear order reasoning tasks (A>B, B>C, C>D, etc.) shows quicker, and more accurate responses to queries on wider (AD) than narrower (AB) pairs on a hypothetical linear mental model (A-B-C-D). Whilst indicative of an analogue representation, research so far did not provide positive evidence for spatial processes in the construction of such models. In a series of seven experiments we report such evidence. Participants respond quicker when the dominant element in a pair is presented on the left (or top) rather than on the right (or bottom). The left-anchoring tendency reverses in a sample with Farsi background (reading/writing from right to left). Alternative explanations and confounds are tested. A theoretical model is proposed that integrates basic assumptions about acquired reading/writing habits as a scaffold for spatial simulation, and primacy/dominance representation within such spatial simulations.

137 words

**Key Words:**.symbolic distance effect (SDE), magnitude processing, linear orders, spatial processing, reading direction, metaphoric blending, symbolic comparison

**Word Count:** 20,830

The present research aims at a better understanding of the representation of rank orders in memory. In particular, it seeks to identify spatial characteristics of such representations. Previous research has often found that after learning a linear rank order such as *A is older than B, B is older than C, C is older than D*, … etc., later test queries about pairs that span wider distances on that order are generally responded to more quickly, and with greater accuracy, than pairs that span narrower distances. For example, participants showed faster and more accurate responses to a query on the pair AD compared to a query on the pair AC, or to a query on AC compared to one on AB (*Symbolic Distance Effect*, SDE, Potts, 1974; Smith & Foos, 1975; Pohl & Schumacher, 1991). Giving it a spatial interpretation, this type of finding has been termed “symbolic distance effect” (SDE), seeing it as indicative of an analogue representation of the order A > B > C > D etc. constructed during learning (Leth-Steensen & Marley, 2000). When activated upon a query, a response can be read off from the representation (Leth-Steensen & Marley, 2000), with wider distances being better discriminable than narrower distances (Holyoak & Patterson, 1981; Huttenlocher, 1968). However, the SDE can also be explained by analogue models without reference to visual discriminability and, therefore, spatial representation. If the overall (neural) activation of each stimulus within A > B > C > D corresponds to the proportion of comparisons in which it dominates another, then after learning, the activation levels will represent the rank order (Leth-Steensen & Marley, 2000), with differences in activation representing the distances between stimuli. Such models also predict that there should be more immediate and stronger response tendencies to queries on wider pairs than to queries on narrower pairs.

It is therefore still unclear to what extent a spatial representation of an order is necessary for distance effects to occur, or even, more mildly, to what extent such effects are reliably associated with spatial representations. In the present research we seek to present arguments and evidence to support the idea that such an association does in fact exist. The question is whether spatial processes are involved when people mentally construct rank order sequences between elements that do not *a priori* stand in any ordered relation with each other, but have to be freshly learned as doing so, based on abstract relational information that by itself does not bear spatial implications.

In general, arguments for the contribution of spatial processes in forming mental representations often rest on the demonstration of lateral asymmetries. Such asymmetries can take the form of compatibility between small and large magnitudes and left-right response key locations. A case in point is the so-called SNARC effect (“spatial numerical association of response codes”) for numerical stimuli which has been argued to be supported by a spatial number line (Gevers, Caessens, & Fias, 2005). In cultures with left-to-right reading and writing systems, such as in Western, English-spoken countries, this line proceeds with increasing magnitude from left to right, whereas in cultures with an opposite right-left-system it proceeds from right to left (Chatterjee, 2001; Dehaene, Bossini, & Giraux, 1993; Maass & Russo, 2003; Tversky, Kugelmass, & Winter, 1991; Zebian, 2005). For example, English speaking participants are faster to give an 'odd vs. even' response to a large number on the right side as compared to the left side, and vice versa for a small number (see also Shaki et al., 2012 for a non-numerical SNARC effect, elaborated on below).

Another recently studied example for spatial processes underlying mental arrangments of abstract orders is time (Boroditsky & Ramscar, 2002). English-spoken participants spontaneously mapped a sequence of events (such as the meals of the day) onto a horizontal line directed rightward, placing earlier events to the left and later events to the right (Fuhrman & Boroditsky, 2010), which was reversed in Hebrew-speaking participants. Spanish speakers responded faster when making judgments on whether words refer to the past or the future when past-related words appeared left and future-related words appeared right on a screen (Ouellet, Santiago, Funes, & Lupianez, 2010; Santiago, Lupianez, Perez, & Funes, 2007), and in Dutch-speakers, months close to the beginning of the year were responded to faster with the left hand than with the right hand, whereas the opposite was found true for months towards the end of the year (Gevers, Reynvoet, & Fias, 2003). Tversky et al. (1991) had children order pictures into temporally ordered stories and found a majority tendency to order these from left to right in English-speaking children, whereas this tendency reversed in Arab and Hebrew children who were used to right-to-left-written languages. However, preliterate kindergarteners did not show any such spatial biases (Dobel, Diesendruck, & Bölte, 2007) which again hints at the tight connection between acquired reading/writing habits and the orientation of the mental time line.

A third instance in which a consistent left-right orientation has been found for a particular type of abstract mental representation is the *good-bad* dimension, whereby *bad* appears to be represented to the left, and *good* to the right (for an overview see Casasanto, 2009). However in this case, it can be argued that linguistic habits are not likely associated with this effect because it is predominantly found in right-handers of all language backgrounds, whereas left-handers, with English background and otherwise, show the reversed pattern. Casasanto (2009) indeed favours a body-specificity explanation, whereby people would tend to associate *good* with the side of their hand with which they can act more fluently.

To summarize, the number line, the time line, and evaluation all provide examples for spatial processes supporting abstract reasoning by providing an oriented dimension onto which the abstract concept is projected. Experimentally, these asymmetries can be understood as indicators for spatial processes assuming that if the spatial orientation of the stimuli on display is in line with the spatial orientation of the mental representations of the same stimuli, then this would lead to quicker processing than when these two orientations run counter to each other.

Left-right as a metaphor of magnitude or primacy/dominance?

In the light of these strands of research we return to the issue of how to gain evidence for spatial processes associated with the construction of linear orders, given that such orders generate SDE's (Potts, 1972, 1974; Riley, 1976; Trabasso, Riley, & Wilson, 1975; see also Barclay, 1973). For the present purpose, it is important to infer from the classical studies that a spatial mental model has analogue characteristics (see Leth-Steensen & Marley, 2000), and that retrieving information from it may be seen as some sort of embodied simulation (Hegarty, 2004; Niedenthal, Barsalou, Winkielman, Krauth-Gruber, & Ric, 2005). Embodied simulations are structures in working memory that are ad-hoc constructed from salient parts of long-term memory (Greeno, 1989; Hegarty, 2004) and, as we believe, use space in various, flexible ways. Basically they are mental models, and the term „embodied simulation" only emphasises the aspect that a bodily experienced, physical dimension (space) is used to construct the model and to define the relations between its constituents.

When some memory content is simulated in a spatial model, for example, in order to generate a judgment, then the salient spatial dimension has to have some meaning. For example, when two memorised people have to be judged as to who is the older in the pair, the spatial dimension might represent age. Or, if a sequence of three events that are supposed to happen next week is put into focus in working memory, the spatial dimension that will serve this particular simulation might have the meaning of time, or priority. The crucial question thus arises what particular metaphor is in use, that is, what particular semantics might be simulated for a given set of stimuli. The body specificity argument (Casasanto, 2009) is restricted to *good-bad*, or, more inclusively, any stimuli or dimensions that are evaluative in nature; but is probably not applicable in general. Therefore, in the more general case of order dimensions with non-evaluative semantics, we will juxtapose two alternative perspectives (1, 2, see below) in order to generate hypotheses. Both alternatives make different assumptions about the metaphors in use, but both rely on the common assumption that people, when constructing mental arrays out of piecemeal information, do this following their learned reading/writing direction, that is, they start on the left side in English-speaking countries. Using English-spoken participants, post-experimental interviews (Huttenlocher, 1968, p. 551) revealed that when, introspectively, these participants did construct horizontal dimensions of non-evaluative meaning, they mostly did so starting on the left side.

(1) The underlying semantics when spatially simulating an ordered sequence such as *A is older than B, B is older than C, C is older than D,* etc., may be *magnitude*. If magnitude is associated with quantification, research from both number and time line domains would predict that people tend to place the youngest (i.e., the "least old") on the left, and the oldest on the right. This would correspond to higher numbers representing larger quantity being placed on the right hand side, as well as greater amounts of time passed being represented on the right hand side.

(2) The underlying semantics when spatially simulating an ordered sequence such as A is older than B, B is older than C, C is older than D, etc., may be *primacy/dominance*. To the extent that primacy in processing (e.g., dealing with the first of a series of elements) is associated with dominance, this argument would predict that the oldest (i.e., the most dominant element) should be placed to the left, and the least dominant element to the right. Casasanto (2009) argued that part of his data, despite the general left-right orientation of *bad-good* amongst right-handers, also showed some independent influence of a tendency to place *good* on the left side. "Linguistic expressions like "the prime example" conflate primacy with goodness (i.e., this phrase can mean the first example, the best example, or both)" (p. 362). If in the general, non-evaluative case, primacy (as triggered by reading/writing habits) is

conflated with dominance, thus yielding a “metaphorical blend” (Casasanto, 2009) between the two, the above prediction follows.

Both perspectives (1) and (2) claim that the construction of the mental order representation starts on the left and proceeds to the right for people with Western reading/writing background. They differ with respect to the treatment of magnitude. In (1), magnitude is as such simulated, thus predicting that magnitude will increase from left to right. In (2), primacy/dominance is simulated, and due to the metaphoric blend between primacy and dominance, greater magnitudes (to the extent that they imply dominance) will be simulated on the left, and lesser magnitudes on the right.

## Non-numerical SNARC effects

A related question has recently been addressed by Shaki, Petrusic and Leth-Steensen (2012). These authors were interested in spatial processes underlying comparative judgments on pairs of stimuli, differing on a given dimension (e.g., two animals of different sizes). They found that left-hand responses were facilitated when “smaller” judgments were required for pairs of relatively small animals (e.g., snail vs. mouse) whereas right-hand responses were facilitated when the same type of judgment (“smaller”) was to be made for relatively large animals (e.g., tiger vs. moose). The authors see this as an indication of a horizontal mental dimension representing size. Notably however, these effects tended to reverse when “larger” judgments were required, that is, left-hand responses were facilitated for large animal pairs and right-hand responses for small animal pairs, which pattern points to an essential influence of instruction (as to the salient pole of dimension) in this type of task. Our approach is different in two respects: We aim at avoiding any sort of instructional influence on the formation of the mental dimension. Instead, we try to find traces of spatial processing when participants construct such a mental model in a situation that would not prompt or cue pole saliency, as further elaborated below. Furthermore, the question here is how rank orders are newly learnt whereas Shaki et al. (2012) deal with order relations represented in, and retrieved from, long-term memory.

There are however aspects of Shaki et al.'s findings that can also be investigated using our approach. Shaki et al. (2012) suggest that within the spatial dimension representing a rank order of stimuli, the semantics of that representation might be aligned with instructions: When instructed to search for "small", *small* appears to be placed to the left and *large* to the right, and vice versa when instructed to search for "large". Notably however, in each of these situations the associated facilitation effect also reverses within the condition; such that, for example, the left-hand advantage for "small" judgments turns into a right-hand advantage for "small" judgments when using relatively large animals for the pairs, instead of relatively small animals. So it appears that, relative to a given anchoring of the size dimension (e.g., small = left), the associated laterality effect is qualified by the ordinal position of the queried pair on that dimension. In the following series of experiments we aim at replicating this signature pattern as a secondary hypothesis, to see whether Shaki et al.'s findings generalise to the present experimental situation which differs from Shaki et al.'s (2012), reflecting the fact that we address the question how ordered sequences are newly acquired and spontaneously represented. In their research, one particular pole of the dimension (small or large) is always made salient before participants see the first of the stimulus pairs. In contrast, in most of our experiments (Experiment 2 onwards), participants will have none of the poles made salient beforehand, but will be left with no prime or cue in order to construct their mental representation of the order dimension.

## Experiment 1: The Left-Anchoring Effect

A first study was conducted to obtain evidence for spatial processes in the construction of a spontaneous, non-cued, mental representation of an ordered sequence.

Following the above reasoning, if the spatial orientation of two stimuli within a display is congruent with the orientation of those same two stimuli in their spatial mental representation, then a response should be made more quickly than when the display orientation is incongruent with the mental representation. The reason for this is that an incongruent display will cause interference with the pre-existing spatial representation (for more details, see General Discussion).

Participants were asked to learn ordered sequences of five fictitious persons A - E per block. Then, in a test phase immediately afterwards, they were presented with all possible pairs such that the names would appear horizontally adjacent on a computer screen. Each order relation had a clear, transitive meaning, implying dominance, e.g., “older” or “taller”, such that “A > C” would always hold if “A > B” and “B > C” was known. This again means that for each possible pair, there was one dominant and one non-dominant element. Responses were made via two horizontally located marked keys on the keyboard, to indicate the side of the dominant element.

As a replication of earlier research on the SDE, accuracy was predicted to increase, and response time for correct responses to decrease, as a function of increasing pair distance between the elements A..E (Potts, 1974; Smith & Foos, 1975; Pohl & Schumacher, 1991). According to the above reasoning contrasting (1) magnitude and (2) primacy/dominance, the expectation from (1) was to find faster response times for correct responses when the dominant element was presented on the right in a pair that was appearing on the screen; however according to (2), response times should be faster when the dominant element was presented on the left side in a pair. As a prediction arising from Shaki et al.’s (2012) findings as described above one should find that any effect, be it (1) or (2), should be qualified (i.e., diminished or even reversed) as a function of the average ordinal position of the pair on the dimension, that is, from the extreme dominant to the extreme non-dominant end.

We also manipulated the distance of the two response keys. Lakens, Schneider, Jostmann and Schubert (2011) found that responses on incongruent Stroop trials were facilitated when participants used response keys located relatively far apart as opposed to close together. In line with the theory of event coding (features of stimulus and response actions are integrated into common representations, see Hommel, Müsseler, Aschersleben, & Prinz, 2001) this result suggests that the distance between the two response keys may have an influence on the actual difficulty of the discrimination between the dominant and the non-dominant element. This in turn raises the question whether, in terms of the motor component of the response involved, spatial structuring of the response options would moderate either the SDE or any potential effect according to the hypotheses (1) or (2).

## Method

### Participants

Fourty-four undergraduate students from Cardiff University, School of Psychology (36 female, eight male, mean age = 19.8 years) took part in the experiment, all with English-spoken backgrounds. They received course credit for their participation. Participants were excluded when they were extreme outliers according to Tukey's criterion (i.e., 3 times the interquartile range above or below the upper or lower quartile, respectively, in the participant sample's distribution of average accuracy rates or average correct response latencies). These exclusion procedures were used in all remaining experiments as well. Four participants were thus discarded from further analyses in the present experiment. Two of them displayed accuracies around .50, and two had abnormally long response times, so the final sample comprised 40 participants.

### Materials

Six English adjectives were used to denote six semantically different transitive relations (*older, richer, taller, smarter, stronger,* and *faster*), to be used in each of the six experimental blocks. In each block, one set of five English first names was randomly assigned to that block (here denoted as A, B, C, D, and E, for the full sets of names see Appendix A). Three of the six name sets were female and three were male. For each participant, the assignment across the six blocks between the relational words and the name sets was freshly determined at random.

As stimuli for learning and testing, all ten possible pairs (AB, AC, …, CE, DE) were prepared in the form "A is *r* than B" where A and B stand for any two names, and *r* stands for one of the above-listed relational adjectives. The display on the screen was either as a full sentence, e.g., "John is taller than Paul" (for the learning phase, see below), or as a name pair, e.g., "John              Paul" with a 22 mm wide gap between the names (for the test phase, see below). Note that amongst stimuli designed for the test phase, pairs AB, BC, CD, and DE represented instances for a 1-step distance; and respectively, pairs AC, BD, and CE for a 2-step distance, pairs AD, BE for a 3-step distance and the pair AE for the maximal 4-step distance. Letters were ASCII with 6 mm maximal height. The gap between the names in the test phase extended 11 mm to the left and to the right of the screen center.

<u>Procedure</u>

After reading instructions, participants were seated approximately 30 cm in front of a computer screen. They were then presented with the learning phase of the first experimental block. In a learning phase, a participant viewed all ten possible pairs twice on the screen, in a self-paced presentation sequence. Within this sequence, all possible pairs occurred once first before all of them were presented again, with the randomization excluding a pair repetition between the two cycles. After this, a test phase followed. A test phase consisted of 40 items, that is, all ten possible combinations presented four times, with the dominant person two times on the left and two times on the right.

Test cycles, invisible to the participant, were programmed such that all ten pairs were presented before the next cycle started. Left- vs. right-orientation of the dominant person was determined randomly for each pair across the four cycles. Response key assignment conditions as narrow (“b” for left and “n” for right) or wide (“a” for left and “6”, on the number pad, for right) were made at random for each participant and for three experimental blocks per condition. These four keys on the keypad were marked with orange (narrow condition) and green (wide condition) labels, and before each block started, an instruction screen told the participant to keep the two index fingers lightly on the respectively coloured keys, in readiness for quick responses. The task was to indicate as quickly and accurately as possible the side where the dominant person was appearing (i.e., the older, taller, etc.). Each pair trial began with a fixation stimulus (“X”) at the centre of the screen, lasting for 1000 ms. After that interval, the pair was presented with an open response interval. There was a 2000 ms blank screen interval between any two consecutive trials.

Learning and test phases as described occurred six times, corresponding to the six experimental blocks. In between blocks, in this and all subsequent experiments, a series of four easy arithmetic problems had to be solved as interpolated task, to clear participant’s short-term memory from the previous set of names. The experiment lasted between 30 and 40 minutes, including debriefing.

## Results

The accuracy and latency data of all reported experiments in this paper were each analysed in two steps. We estimated linear mixed models (for the accuracy data: generalized linear mixed models with logistic link function) with *participants* as random factors, and first determined which random structure would best fit the data. Subsequently, a final model with appropriate random effects was used to evaluate fixed effects (see Jaeger, 2008; Judd, Westfall, & Kenny, 2012). The strategy for selecting a model with appropriate random-effects structure is described in Appendix B, along with information about the particular random-effect structure adopted for each model in each experiment. Effect sizes (Cohen's *d*) are reported across all experiments for those effects that are interpreted as relevant to the main hypothesis, that is, the laterality effect[1]. This pertains mostly to response latencies, with one exception, Experiment 7, where accuracies are interpreted as carrying the laterality effect.

Average ordinal position was used in all models as a continuous predictor, the other independent variables were effect-coded as factors.

Accuracy

The overall error level was 5.8%, across all participants and all test pairs. The final model to be evaluated contained fixed effects for key distance (narrow vs. wide), side of dominant element (dominant element left vs. right), pair distance (1 step, ..., 4 steps), and type of relation (older, taller, etc.) and the interactions of these factors. It also had the standardised average ordinal position of the test pair, as well as its interaction with dominant side, as predictors. For example, within the five elements of the order, pair AB had an average ordinal position of 1.5, CE one of 4, AE one of 3, and DE one of 4.5.

There were significant fixed factor effects for pair distance, $\chi^2[df = 3] = 212.09$; $p < .0001$, indicating that responses were more correct with wider pair distance, and for average ordinal position, $\chi^2[df = 1] = 51.00$; $p < .0001$, indicating an increase in accuracy from the dominant to the non-dominant pole of the dimension, $\beta = .28$. Amongst all interaction terms, only the triple interaction between key distance, pair distance, and type of relation was significant, $\chi^2[df = 15] = 25.04$; $p < .05$. See Figure 1 for the mean accuracy as a function of side of dominant element and pair distance (in this figure and all further figures and tables, means are collapsed across type of relation, for clarity of presentation. No systematic effects were associated with this factor in any experiment).

Response latencies

For correct responses, latency data were trimmed according to the Tukey criterion based on excluding outliers with values larger (smaller) than the upper (lower) quartile plus (minus) 1.5 times the interquartile range in the individual's distribution of latencies (see Clark-Carter, 2004, Chapter 9). The final model to be evaluated had the same fixed effect structure as the one just reported for accuracy (for its random effect structure see Appendix A). In this model, three significant main effects occurred, that is, for side of dominant element, $F(1,8150.68) = 36.63$; $p < .0001$, *Cohen's d* = .16, showing that responses were quicker when the dominant element was displayed on the left side; for pair distance, $F(3,36.02) = 42.13$; $p < .0001$, showing that responses were faster the wider the distance of the two names in the pair on the hypothesised dimension (for means, see Figure 2); and finally, average ordinal position of the pair, $F(1,8182.85) = 571.22$; $p < .0001$, which means that overall, response speed on average got slower the more the queried pair was located to the non-dominant end of the dimension, $\beta = 115.555$. Amongst all interaction terms, only side of dominant element x average ordinal position was significant, $F(1,8147.61) = 8.17$; $p = .004$), meaning that the response advantage for left-presentation of the dominant element tended to diminish across pairs which were more situated towards the non-dominant end of the dimension, $\beta = 13.762$.

There was an unpredicted, significant triple interaction of response key distance with pair distance and type of relation.

## Discussion

The classical distance effect (SDE) was replicated. Queries on pairs of wider distances were responded to with greater speed and accuracy than those of narrower distances (Potts, 1974; Smith & Foos, 1975; Pohl & Schumacher, 1991). This result can be taken as indicative of an analogue representation being formed out of the initial piecemeal information that was learned (Holyoak & Patterson, 1981; Leth-Steensen & Marley, 2000). In addition, the present data provide evidence for the notion that spatial processes might be associated with, or involved in, the construction of analogue representations of linear orders, because a laterality effect was obtained (for a related effect see also Shaki et al., 2012, and below). When the dominant element in a pair was presented on the left side, a correct response was generated more quickly than when the dominant element was on the right side. Presumably, when constructing an ordered mental model of the sort A – B – C – D – E the maximum (i.e., the most dominant element A) of the dimension tends to be mentally located, or anchored, on the left side. This "left-anchoring" phenomenon is in line with the assumption that not magnitude per se, but primacy (as metaphorically conflated with dominance) is simulated via the spatial dimension left-right, following established reading/writing habits.

Response key distance made no difference in the present experimental setting. Whether the two keys used to indicate the side of the dominant element were close together or far apart on the keyboard did not matter by itself, nor did it interact with the SDE or the left-anchoring effect. This indicates that processes associated with the motor component of the response involved, that is, executive response processes as opposed to those in the service of mental model construction proper, are not likely to influence the observed spatial anchoring phenomenon, at least not in the sense as observed by Lakens et al. (2011).

The data on average ordinal position of the queried pair, entered as a continuous predictor, can be interpreted as showing two tendencies. First, there appears to be a tendency of speed-accuracy trade-off, in that responses overall are quickest, but also relatively most error-prone, when participants answer queries about pairs close to the dominant pole of the hypothetical dimension. Responses become more accurate, and slower, across the levels of ordinal position, that is, towards the non-dominant pole. Second, as the interaction with side of dominant element shows, the left-anchoring phenomenon tends to weaken as a function of positional level on the dimension from dominant to non-dominant. This effect bears resemblance to the one observed by Shaki et al. (2012) as discussed above. In other words, the left-side advantage of the dominant element in a pair is most pronounced when that pair is located very close to the maximum dominant pole on the dimension, and gets slightly washed out as stimulus pairs move away from it towards the other pole. Unlike Shaki et al. (2012) we do not observe a full reversal of the effect (to a right-side advantage) as ordinal positions approach the non-dominant pole, but the tendency observed here could be seen as germane to their reported phenomenon.

The literature on the SDE suggests that the grammatically minimal and the grammatically maximal element within the order, that is, the “end elements” (Leth-Steensen & Marley, 2000), may play a special role, in that end elements are particularly fast to be responded to (Banks, 1977; Moyer & Dumais, 1978; Trabasso et al., 1975). It has been argued that participants using “end anchor processing strategies” could make a comparative judgment involving an end element quickly. At test, they would identify an end element and generate a response on the basis of its status as extreme element alone, that is, without having to further inspect its relation to other elements in the order representation (Potts, 1972, 1974). In case of the present study, this yields the prediction that, to the extent that the observed laterality effects are influenced by “end anchor processing strategies” (Potts, 1972, 1974) and participants, according to their reading habit, have a tendency to scan the name pair on the screen from left to right, they would exhibit a left-anchoring effect. For when a pair containing the maximum end person is presented with the maximum end person placed on the *left* side, participants would not have to check the other person on the right side, but could just memorize the identity of that particular end person and generate a response from it.

A simplified mixed-model analysis of the response times was therefore conducted in which all test stimuli were excluded that contained an end person, maximum or minimum, to assess whether the observed overall left-anchoring effect was influenced by “end anchor processing strategies”. The analysis followed a simplified design, that is, it did not account for average ordinal position of pairs, and it had only two levels for the Pair Distance factor since the two end persons had been removed. This analysis yielded an effect of pair distance, $F(1,38.78) = 40.81$, $p < .0001$, and an effect of side of dominant element, $F(1,2373.11) = 18.20$, $p < .0001$. No other effects were significant. This means that left-anchoring as observed in this experiment does not crucially depend on the inclusion of the end elements in the ordered array[2].

## Experiment 2: The Role of Presentational Factors

For the ease of mental model construction (see Potts, 1974; Smith & Foos, 1975), all stimulus pairs used in Experiment 1 had followed the same grammatical structure. That is, the sentence subject in “A is *r* than B” (with *r* representing the relational adjective, see above) was the dominant element in the pair. Due to this method of presentation, by which the dominant element would always appear on the left, it is possible that the origin for the observed left-anchoring effect was not the construction of a mental linear array via spatial processes per se, but a perceptually driven memory effect whereby dominance was associated with location on the left during presentation in the learning phase. In order to address this alternative explanation it is crucial to show that the observed left-anchoring effect persists in a condition without perceptual bias concerning the orientation of the order dimensions during learning. Therefore, in Experiment 2, stimuli of the form “A is *r* than B” (dominant element left) were used as well as stimuli of the form “B is *less r* than A” (dominant element right), as tested in three groups: during learning, Group 1 received left-dominant stimuli throughout, Group 2 received right-dominant stimuli throughout, and Group 3 received 50% left-dominant and 50% right-dominant stimuli randomly interspersed. This latter group is the crucial one in which to demonstrate a left-anchoring effect for the maxima of the order dimensions.

The response key distance manipulation was dropped in these and all following experiments on the basis of the null findings from Experiment 1, such that all participants from now on (except in Experiments 5 and 6 as explained below) responded using the “b” and “n” keys for left and right.

Participants

Sixty-three undergraduate students from Cardiff University, School of Psychology (59 female, four male, mean age = 19.1 years) took part in the experiment, all with English-spoken backgrounds. They received course credit for their participation. They were randomly assigned to the three groups, such that there were 20 participants in Group 1 (left-dominant), 21 in Group 2 (right-dominant), and 22 in Group 3 (50:50). Four participants were discarded from further analyses because of low accuracies. The final sample comprised 59 participants, 18 in Group 1, 19 in Group 2, and 22 in Group 3.

Materials

Similar materials were used as in Experiment 1, with the following modifications. In the learning phase, participants in Group 1 saw only pairs of the form “A is *r* than B” (dominant element always left). Participants in Group 2 saw only pairs of the form “B is *less r* than A” (dominant element always right). Participants in Group 3 saw half of the pairs in the form “A is *r* than B”, and half of the pairs in the form “B is *less r* than A”, whereby in this group, materials were distributed across the two cycles of the learning phase such that in each cycle of the ten possible pairs, five would appear in either orientation. If a particular pair appeared left-dominant in cycle one, it would appear right-dominant in cycle two, and vice versa. Apart from this, pair presentation during learning was random in all three groups, as in Experiment 1. Note that Group 1 constitutes a direct replication of Experiment 1.

Procedure

Procedures and dependent measurements were identical to Experiment 1. The experiment lasted between 30 and 40 minutes, including debriefing.

Results

Accuracy

The overall error level was 16.5%, across all participants and all test pairs. The final model had fixed effects for group (left-dominant learning vs. right-dominant learning vs. 50:50 learning), pair distance (1 step, ..., 4 steps), side of dominant element (left vs. right), and type of relation (*older*, ..., *faster*), see Table 1 for the means (collapsed across type of relation). Additionally, standardised average ordinal position of the test pair plus its interaction with dominant side were entered as predictors. Again, Pair Distance was associated with a significant effect, $\chi^2[df = 3] = 98.71$; $p < .0001$, replicating the SDE. An unexpected triple interaction between pair group, pair distance, and type of relation, $\chi^2[df = 30] = 45.91$; $p = .03$, indicated that the left-dominant group (Group 1) was slightly more accurate than the 50:50-group (Group 3) at all distances and types of relation except the narrowest distance for the “faster”-Relation, and that the 50:50-group (Group 3) was slightly more accurate than the right-dominant group (Group 2) at all distances and types of relation except the widest distance for the “smarter”- relation and the narrowest distance for the “older”-relation. There were no other significant effects.

Response latencies

The final model had the same fixed effect structure as the one for accuracies. There was a main effect of pair distance, $F(3,53.49) = 68.65$, $p < .0001$, showing the classical distance effect. Pairs of adjacent position on the hypothetical array ($M_{1\ step}$ = 871 ms) required more time to be responded to than pairs of wider distance ($M_{2\ step}$ = 794 *ms*; $M_{3\ step}$ = 692 *ms*; $M_{4\ step}$ = 595 ms). Furthermore, there was a significant effect of side of dominant element, $F(1,66.34) = 8.09$, $p = .006$, replicating the left-anchoring effect found in Experiment 1.

Dominant elements presented on the left side generated faster correct responses than dominant elements presented on the right side ($M_{left}$ = 720 ms, *vs.* $M_{right}$ = 759 ms). Average ordinal position of the pair had a significant effect, $F(1,11001.43) = 449.80$; $p < .0001$, $\beta$ = 101.509, and tended to interact with side of the dominant element, $F(1,10950.18) = 3.36$; $p = .07$. The response advantage for left-presentation of the dominant element tended to diminish across pairs which were more situated towards the non-dominant end of the dimension, $\beta$ = 8.71. No other effects were obtained.

The crucial left-anchoring effect was also found significant when testing Group 1 (left-dominant) separately, $F(1,23.51) = 9.96$, $p = .004$, *Cohen's d* = .15, who had seen only left-dominant learning items, as well as for Group 3 separately, $F(1,26.98) = 8.32$, $p = .008$, *Cohen's d* = .12, who had seen 50:50 left- and right-dominant items during learning. The effect was however found non-significant when analyzing Group 2 (right-dominant) alone who had seen only right-dominant learning items, $F(1,19.86) = .14$, $p = .71$, *Cohen's d* = .003. In the global analysis, the interaction between group and side of dominant element did not reach significance, $F(2,66.35) = 0.71$, $p = .49$.

.

## Discussion

Overall, response times in this study were shorter and accuracies lower than in Experiment 1. This is possibly due to the fact that in the present experiment the Response Key Distance factor had been dropped as within-participant factor varying between the blocks, simplifying the task and leading perhaps to a shift in overall speed-accuracy settings.

In a situation where presentation conditions during learning did not give any systematic hint on the spatial orientation of the dimension used to construct their mental array (Group 3), participants' response latencies nevertheless exhibited a clear left-anchoring effect. This supports the idea that the present left-anchoring phenomenon is a spontaneous tendency, not perceptually triggered by presentation mode, nor by the grammatical surface structure of the stimuli used in Experiment 1 in which the dominant element was always on the left. Rather, we believe that the tendency to left-anchor the maximum of an abstract dimension reflects a spatial component associated with the process of constructing an analogue representation of an ordered sequence of stimuli (Huttenlocher, 1968; Leth-Steensen & Marley, 2000; Sedek & von Hecker, 2004). This spatial process in turn is presumably triggered by the habitual reading/writing direction. The replicated observation that the maximum, and not the minimum, of the dimension is anchored to the left suggests that the simulated entity in question (see Hegarty, 2004; Niedenthal et al., 2005) is primacy rather than magnitude per se (Casasanto, 2009).

The pattern in Group 1 (left-dominant, $M_{left}$ = 664 ms, vs. $M_{right}$ = 727 ms) who saw only left-dominant learning items parallels the pattern in Group 3 ($M_{left}$ = 643 ms, vs. $M_{right}$ = 693 ms); however, Group 2 members who saw only right-dominant learning items did not show a significant effect of Display Direction when tested separately. The closeness of the means in this group ($M_{left}$ = 863 ms, vs. $M_{right}$ = 864 ms) suggests that the right dominant presentation induces a counteracting directional bias in at least some Group 2 members that may eliminate the left-anchoring effect. In line with this speculation, accuracies were slightly lower overall in Experiment 2 than in Experiment 1, perhaps in part due to Groups 2 and 3 who saw learning items in an orientation incongruent with a left-anchored maximum ($M_{Group1}$ = .868; $M_{Group2}$ = .802; $M_{Group3}$ = .833). Also, looking at the latency data, the standard deviation in random slopes across participants, associated with the side-of-dominant-element factor, is considerably larger (76.90) in Group 2 (right-dominant) than the corresponding standard deviations in both Groups 1 (left-dominant, 17.96) and 3 (50:50, 26.94). Whereas such a moderation may be addressed in future research, the central result from the present study supports the notion that when there is no directional bias induced by presentation factors during the learning phase (Group 3), people with English-speaking backgrounds spontaneously tend to construct spatial models of an order dimension with the maximum positioned on the left side within the spatial representation.

In terms of the average ordinal position of the queried pair, there was no evidence, in this experiment, for a speed-accuracy trade-off: There was a main effect of ordinal position for latencies, but no main effect of ordinal position for accuracies. On the other hand, the interaction with side of dominant element did replicate as a tendency, showing that the left-side advantage of the dominant element in a pair diminishes as ordinal positions move farther away from the dominant pole on the dimension (see Shaki et al., 2012).

## Experiment 3: The Role of Response Factors

For this and all following experiments (except Experiment 4b), conditions in the learning phase were kept the same as in Group 3 (50:50) from the previous experiment, that is, participants saw a perceptually unbiased random sequence of stimuli in which the dominant element in a pair was either left or right (or, up or down in Experiments 5, 6), corresponding to half of the pairs being presented in the form "A is *r* than B", and half of the pairs in the form "B is *less r* than A".

The basic argument of the present research is that laterality effects such as the observed left-anchoring for maxima provide support for the idea that spatial processes are involved in the construction of analogue mental representations of order. If it is correct that people use spatial reasoning to mentally establish the order dimension in question by placing its maximum to the left, then one should be able to find evidence for such reasoning when eliciting responses at both sides of the dimension. That is, participants may be asked to identify the *older, richer, taller*, etc. in a pair (the grammatically dominant element), or they may be alternatively asked to identify the *less old*, the *less rich*, the *less tall*, etc., (the grammatically non-dominant element). Experiments 1 and 2 used only the former response format; the present one compares both by introducing response format as a group factor.

The prediction for the latter, the grammatically non-dominant, "*less r*", response format is the same as for the former, grammatically dominant, format (see Schubert, 2005, his Experiment 2). Responses should be quicker for pairs presented spatially congruent to the hypothetical mental array, in other words, displaying the dominant element on the left side, as compared the right side, in a test pair.

## Method

### Participants

Forty-three undergraduate students from Cardiff University, School of Psychology (35 female, eight male, mean age = 21.1 years) took part in the experiment, all with English-spoken backgrounds. They received course credit for their participation. They were randomly assigned to the two groups, such that there were 23 participants in Group 1, and 20 in Group 2. Three participants were discarded from further analyses because of low accuracies from Group and one because of exceptionally long latencies from Group 2. The final sample comprised 20 participants in Group 1 and 19 in Group 2.

### Materials

In the learning phase, the same materials were used as in Group 3 from Experiment 2, that is, participants in both present groups saw half of the pairs in the form "A is *r* than B", and half of the pairs in the form "B is *less r* than A". Materials in the test phase were the same as in Experiment 1 and 2.

### Procedure

Procedures and dependent measures were identical to Experiment 2, except for response format in the test phase: Participants in Group 1 were asked to quickly and accurately identify the *older, richer, taller,* etc. person (grammatically dominant), whereas participants in Group

2 were asked to quickly and accurately identify the *less old*, *less rich*, *less tall*, etc., person in a pair (grammatically non-dominant). The experiment lasted between 30 and 40 minutes, including debriefing.

## Results

### Accuracy

The overall error level was 15.8%. The final model had fixed effects for group (dominant testing vs. non-dominant testing, pair distance (1 step, ..., 4 steps), side of dominant element (left vs. right), and type of relation (*older*, …, *faster*), see Table 2 for means (collapsed across type of relation). Pair distance yielded a significant effect, $\chi^2[df = 3] = 61.99$; $p < .0001$, replicating the SDE ($M_{1\ step} = .750$; $M_{2\ step} = .829$; $M_{3\ step} = .872$; $M_{4\ step} = .917$). There was an unpredicted main effect of type of relation, $\chi^2[df = 5] = 12.18$; $p = .03$, indicating that participants were particularly accurate when the comparators were "richer" (.88) and "faster" (.91). An unpredicted interaction of group and ordinal position, $\chi^2[df = 1] = 4.40$; $p = .04$, revealed that participants who had to find the dominant element were slightly better at the dominant end of the dimension, whereas participants who had to find the non-dominant element were better at the non-dominant end, $\beta = -6.59$. Group also entered a triple interaction with side of dominant element and type of relation, $\chi^2[df = 5] = 13.19$; $p = .02$, showing that the above two-way interaction was more pronounced for "smarter" and "faster" than for the other relations. There were no other significant effects.

### Response latencies

The final model had the same fixed effect structure as the one for accuracies (see Table 2 for means). There were significant main effects for group, $F(1,37.22) = 5.14$, $p = .03$, indicating faster responses when participants were to find the dominant person in a pair ($M_{dominant} = 913$ ms, *vs.* $M_{non\text{-}dominant} = 1138$ ms), and for side of dominant element, replicating the left-anchoring effect, $F(1,45.16) = 6.81$, $p < .01$. Dominant elements presented on the left side generated faster correct responses than dominant elements presented on the right side ($M_{left}$ = 955 ms, *vs.* $M_{right}$ = 997 ms). A significant main effect of pair distance, $F(3,7416.48) = 121.00$, $p < .0001$, again demonstrated faster correct responding the wider the pair distance (SDE). Pairs of adjacent position on the hypothetical array ($M_{1\ step}$ = 1118 ms) required more time to respond than pairs of wider distance ($M_{2\ step}$ = 1041 ms; $M_{3\ step}$ = 943 ms; $M_{4\ step}$ = 804 ms). The average ordinal position of the pair had a significant effect, $F(1,7454.64) = 7.65$, $p = .006$, , $\beta = 15.36$, and showed a tendency to interact with side of dominant element, $F(1,7423.49) = 2.97$, $p = .08$. The left-anchoring effect in the latencies diminishes in sizes the more a given pair is positioned towards the non-dominant pole, $\beta = 9.53$.

The crucial left-anchoring effect was found significant when testing Group 1 (dominant responding) separately, $F(1,22.16) = 11.83$, $p = .002$, *Cohen's d* = .21, but failed to reach significance in Group 2 (non-dominant responding) when tested separately, $F(1,21.49) =.35$, $p = .56$, *Cohen's d* = .03[3]. In the global analysis, the interaction between group and side of dominant element did not reach significance, $F(1,45.17) = 2.38$, $p = .13$.

## Discussion

The SDE and the left-anchoring effect replicated again. As previous research has shown, making comparative or evaluative judgments in the direction of non-dominant to dominant appears to be more difficult than when the test format probes the opposite direction (Schriefers, 1990; Schubert, 2005; Van der Schoot, Bakker Arkema, Horsley, & Van Lieshout, 2009). This might depend on the particular study context, as a result of the dominant end having clearer evaluative implications when it is also the linguistically unmarked version of the dimension[4] (see Hamilton & Deese, 1971), or as a result of participants being more unfamiliar with reasoning at the grammatically non-dominant end of a dimension (Schubert, 2005). In light of this, it is interesting to see that when analysing the two groups separately, the directional effect was not significant in Group 2 who responded in a non-dominant way, as compared to a significant effect in Group 1 who responded to test questions phrased in the direction from dominant to non-dominant. In the present case, responding in the former direction (Group 2) also means responding from the perspective of the marked end of the dimension (because we are using unmarked adjectives). Earlier research has shown that participants find it more difficult, and are slower (which also fits our data), when working from the marked perspective on a dimension. Thus, judgments at the marked end might involve more elaborate thinking with the potential to mask the influence of any spatial input. In the context of sentence comprehension, Sherman (1973, 1976) argued that processing at the marked end imposes more cognitive load than at the unmarked end because marked stimuli are often treated as a negation of the unmarked version which induces additional load. Participants may also be less familiar with making judgments from the marked perspective on a dimension (see Schubert, 2005) which would add more error variance, making it difficult to detect an existing spatial effect[5].

It is possible that semantic congruity might have contributed to the different patterns in the two groups: Participants who were searching for the dominant element tended to be more accurate at the dominant end of the dimension, whereas participants who were searching for the non-dominant element were more accurate at the non-dominant end. This effect has been repeatedly found in the literature, although mostly for response latencies and only rarely for accuracies. According to an early interpretation, such an effect may reflect an expectancy held on the basis that the comparator is known prior to the stimulus pair (Moyer & Dumais, 1978, for a review). More recently, the effect has been related to varying degrees of discriminability between stimuli close or distant from the queried end of the dimension (Chen, Lu, & Holyoak, 2014; Marks, 1972).

Again, we found some evidence for the influence of ordinal position on the hypothetical dimension. The left-anchoring effect in the latencies was reduced at ordinal positions closer to the non-dominant pole. We interpret this phenomenon as an additional signature of the anchoring, possibly indicating that the impact of the dimensional layout (i.e., maximum=left) on reasoning is most pronounced when the reasoning is directed at elements close to the very pole that also serves as the anchor. Whereas Shaki et al. (2012), observing a similar phenomenon, see the anchoring as a result of prior instruction, we see it as a result of a spontaneous process, as triggered by reading/writing habits.

## Experiment 4a and 4b: The Role of Linguistic Markedness

The data so far are in support of the existence of a spatial component in the mental construction of linear orders, that is, they are particularly supportive of position (2) as outlined in the Introduction. According to this view, the underlying semantics when spatially simulating an ordered sequence is *primacy* in a metaphoric blend with dominance, but not the descriptive magnitude of the dimension per se. This explanation makes two assumptions that need to be tested in their own right: First, the spatial component of the construction process is triggered to start from the left for Westerners, according to primacy in reading/writing (this to be addressed in Experiment 7). Second, in line with Casasanto (2009) a "metaphorical blend" takes place, that is, the semantics of primacy by itself implies dominance and gets conflated with the meaning of the magnitude described by the particular dimension at hand: The *older*, *taller*, *richer*, etc. in a pair can be seen as dominant and by conflation, therefore, as "primary", which yields a left-anchoring of the spatially generated dimension. This second assumption is addressed in the present experiment, the rationale of which derives from the concept of dominance.

Dominance is so far underspecified, because one may understand dominance within the pairs in two different ways: (1) Dominance may be *grammatical* in terms of comparatives and superlatives, by which the *older* person dominates the *less old* person in the same way as the *younger* person dominates the *less young*. According to this, the *oldest* as much as the *youngest* person should always be placed to the left of the spatial dimension. (2) Alternatively, dominance may be more closely related to the meaning of the magnitude on the particular dimension in question. In this case, the *older* person dominates the *less old* person because the older person has more age (*old* denoting the unmarked dimension as compared to *young*, see Hamilton & Deese, 1971), in which case "more" means an *asset of magnitude* on the dimension of age. The same holds for all other dimensions used in our experiments so far, that is, *rich, tall, smart, strong, fast,* which all reflect assets of magnitude on those dimensions. However, comparisons using the words young, poor, short, dumb, weak, and slow reflect the marked dimension (see Hamilton & Deese, 1971), and as such mean a lack of magnitude on the particular dimension. The *younger* person, if it is a matter of magnitude-related dominance and not grammatical dominance, would not dominate the *less young*. Thus, if we accept dominance to mean that an asset of some positive magnitude is implied, it stands to reason that the semantics of primacy should more easily conflate with semantics of positive assets in magnitude (unmarked versions of our set of adjectives) than with semantics referring to a lack in magnitude (marked versions).

The present two experiments (4a and 4b) compare both versions, unmarked and marked, of the six dimensions used so far. If the *metaphorical blend* assumption (Casasanto, 2009) is correct as part of our explanation of the observed left-anchoring effect, combined with dominance understood as implying positive magnitude on those dimensions we use, then a metaphorical blend is more likely to occur between primacy and the sense of dominance triggered by unmarked words (implying assets of magnitude, e.g., *older, taller, stronger*) than between primacy and marked words (implying a lack of magnitude, e.g., *younger, shorter, weaker*). The left-anchoring effect should therefore be more pronounced when using the former than when using the latter. In the latter case, a left-anchoring effect should be at most weak, or even non-existing. Alternatively, if left-anchoring effects of equal strengths were observed for unmarked and marked dimensions, this would still be consistent with the idea of grammatical dominance as outlined above. Experiment 4a uses a learning phase methodology as before whereas Experiment 4b uses centralized presentation in the learning phase as an alternative.

## 4a: Method

### Participants

Forty-six undergraduate students from the University of Freiburg (30 female, 13 male, mean age = 23.1 years) took part in the experiment, all but one with German-spoken backgrounds (one had Turkish-spoken background which is a language written and read from left to right. They received course credit or €5.00 for their participation. They were randomly assigned to the two groups, such there were 22 participants in Group 1, and 24 in Group 2. Three participants were discarded from further analyses because of low accuracies (two from Group 1, and one from Group 2). The final sample comprised 43 participants, 20 in Group 1 and 23 in Group 2.

### Materials

For the unmarked condition (Group 1) the same six dimensions were used as in the previous studies (*older*, *richer*, *taller*, *smarter*, *stronger*, and *faster*), with all materials translated into German. For the marked condition (Group 2), German equivalents for *younger, poorer, shorter, dumber, weaker,* and *slower,* were used, that is, the corresponding marked terms for the above six dimensions. In terms of data analysis for this experiment and Experiment 4b, the marked dimensional comparators are technically treated in the same (grammatical) way as the unmarked. That is, in a condition where “the dominant element is on the left”, it would mean that, for example “the younger person is on the left”, as much as, respectively, “the older person is on the left”. Therefore in terms of results, if grammatical dominance holds for participants’ representations, then a side-of-dominant-element main effect is expected to be significant across both groups. However, if dominance based on assets of magnitude holds, dominance will not be associated with the grammatical superlative of the comparator in the marked condition, and one would therefore expect an interaction between side of dominant element and group.

Procedure

Procedures and dependent measures were identical to Experiment 3, except in the test phase, participants were asked to quickly and accurately identify the *older, richer, taller,* etc. person in a pair (Group 1, unmarked response format), respectively, the *younger, poorer, shorter,* etc. person in a pair (Group 2, marked response format). The experiment lasted between 30 and 40 minutes, including debriefing.

## 4a: Results and Discussion

Accuracy

The overall error level (i.e., pressing the incorrect key) was 13.5%, across all participants and all test pairs. The selected final model comprised the following fixed factors and their interactions: Group (unmarked vs. marked order dimension), pair distance (1 step, ..., 4 steps), side of dominant element (left vs. right), and type of relation (*older*, …, *faster*), see Table 3a for means (collapsed across type of relation). Group 1, working with unmarked dimensions, performed more accurately overall ($M_{unmarked}$ = .910) than Group 2, working with marked dimensions ($M_{marked}$ = .821), $\chi^2[df = 1] = 17.71$; $p < .0001$. A significant group x pair distance interaction, $\chi^2[df = 3] = 10.89$; $p < .01$, indicated that the performance difference between the two groups grew smaller with increasing pair distance on the hypothetical order. This is also expressed in a significant group x average ordinal position interaction, $\chi^2[df = 1] = 5.77$; $p = .02$, showing that the difference in accuracy between the two groups is minimal at medium ordinal positions. Note that the average ordinal position factor is confounded with distance: Pairs with the extreme ordinal positions 1.5 (AB) and 4.5 (DE) represent narrower distances than the average pairs representing medium ordinal positions 2.5 (AD, BC), 3 (BD) or 3.5 (BE, CD), such that, given that medium ordinal positions at the same time, on average, represent wider distances, the above interaction might just reflect a different angle on the same phenomenon as expressed in the group x pair distance interaction reported above. There were no further effects involving Group. There was also a significant main effect of pair distance, $\chi^2[df = 3] = 64.96$; $p < .0001$, replicating the SDE ($M_{1\ step} = .779$; $M_{2\ step} = .861$; $M_{3\ step} = .893$; $M_{4\ step} = .929$). There were no other significant effects.

Response latencies

The data were submitted to a linear mixed model with fixed factor structure as above (for means see Table 3a). Pair distance proved again significant, $F(3,38.59) = 34.49$, $p < .0001$, replicating the SDE, ($M_{1\ step} = 1491$ ms; $M_{2\ step} = 1406$ ms; $M_{3\ step} = 1225$ ms; $M_{4\ step} = 1097$ ms). There was a significant overall main effect of side of dominant element, $F(1,8192.90) = 7.08$, $p = .008$, showing that dominant elements presented on the left side generated faster correct responses than dominant elements presented on the right side ($M_{left} = 1285$ ms, *vs.* $M_{right} = 1328$ ms). When testing group 1 (unmarked dimensions) separately, this main effect was significant, $F(1,25.96) = 6.96$, $p < .01$, *Cohen's d* = .11, whereas it failed to reach significance in group 2 (marked dimensions) tested separately, $F(1,27.98) = 0.15$, $p = .70$, *Cohen's d* = .01, see Figure 3. Thus, left-anchoring was present in the unmarked group, whereas in the marked group no laterality effect whatsoever was observed. In none of the separate group analyses did the interaction between side of dominant element and ordinal position reach significance (in both cases p < .43, such that it appears unlikely that the failure to find an effect of side of dominant element in group 2 was due to a laterality effect reversing between the two ends of the ordering. In the overall model, the interaction of group by side of dominant element was marginally significant, $F(1,8192.84) = 3.15$, $p = .08$.

## 4b: Method

### Participants

Fifty-one undergraduate students from the University of Freiburg (26 female, 25 male, mean age = 23.4 years) took part in the experiment, all with German-spoken background. They received course credit or €5.00 for their participation. They were randomly assigned to the two groups, such there were 26 participants in Group 1, and 25 in Group 2. Three participants were discarded from further analyses because of low accuracies (one from Group 1, and two from Group 2). The final sample comprised 48 participants, 25 in Group 1 and 23 in Group 2.

### Materials

The same materials as previously were used for the six dimensions (*older, richer, taller, smarter, stronger,* and *faster,* and their marked counterparts), with all materials translated into German.

### Procedure

Procedures and dependent measures were identical to Experiment 4a, with some exceptions, concerning the learning phase. The aim was to use an alternative way of avoiding any directional priming through the mode of visual presentation. In the instructions, care was taken to avoid reference to any possible prioritization amongst “left” and “right”. Participants were instructed, for the learning phase, to watch sequences of two names (1.5s each) presented centrally[6] after a 1000 ms fixation cross, and separated by a blank screen for 800 ms. They were told to understand this sequence such that the first person should be seen as dominant with respect to the dimension in question, as indicated permanently on top of the screen (e.g., "The first person is *stronger*"). Learning pairs were divided by a 2000 ms blank screen. In the test phase, participants were asked to quickly and accurately identify the *older, richer, taller*, etc. person in a pair (*younger, poorer, shorter*, etc., person in the group with marked order dimension) as presented "side by side", and to indicate their choice by use of "one of the marked arrow keys".

The experiment lasted between 30 and 40 minutes, including debriefing.

4b: Results

Accuracy

The overall error level was 18.25%. The final model comprised the following fixed factors and their interactions: Group (unmarked vs. marked order dimension), pair distance (1 step, ..., 4 steps), side of dominant element (left vs. right), and type of relation (*older*, …, *faster*), see Table 3b for means (collapsed across type of relation). Side of dominant element yielded a significant main effect, $\chi^2[df = 1] = 3.87$; $p < .05$, replicating the left anchoring effect in an experimental setting that used only centralised presentation during learning. Tested separately per group, this effect was marginally significant in Group 1, $\chi^2[df = 1] = 3.58$; $p = .06$, and but not significant in Group 2, $\chi2[\mathrm{df} = 1] = 1.05$; $p = .31$. The only further significant effect was for pair distance, $\chi^2[df = 3] = 66.57$; $p < .0001$, replicating the SDE.

Response latencies

The data were submitted to a linear mixed model with fixed factor structure as above (for means see Table 3b). Side of dominant element was significant, $F(1,8764.38) = 4.13$, $p =$

.04, indicating faster correct responding when the dominant element was presented to the left in a pair. Pair distance was also significant, $F(3,43.53) = 26.47$, $p < .0001$, as was average ordinal position, $F(1,8802.11) = 489.24$, $p < .0001$, showing an increase in response latency as pairs of elements move from the dominant to the non-dominant pole, $\beta = 135.24$. When testing group 1 (unmarked dimensions) separately, the laterality main effect was significant, $F(1,4596.06) = 7.17$, $p = .007$, *Cohen's d* = .08, whereas this was not the case in group 2 (marked dimensions) tested separately, $F(1,4147.36) = 0.06$, $p = .80$, *Cohen's d* = .004, see Figure 4. So, with centralized presentation during learning, a spontaneous left-anchoring was present in the unmarked group, whereas in the marked group no laterality effect whatsoever was observed. Moreover, in none of the separate group analyses did the interaction between side of dominant element and ordinal position reach significance (in both cases p < .35, such that it appears unlikely that the failure to find an effect of side of dominant element in group 2 was due to a laterality effect reversing between the two ends of the ordering. In the overall model, the interaction of group by side of dominant element was visible as a tendency, $F(1,8764.37) = 2.36$, $p = .12$.

## Discussion

The present two experiments addressed one of the assumptions made within our explanation for the left-anchoring effect, namely, that a “metaphorical blend” (Casasanto, 2009) would occur between the primacy as triggered by reading/writing habit and dominance in terms of the semantics of the dimension in question. Such a blending, as was hypothesised, should occur in a case where the dimension reflects an asset of magnitude but not to the same degree when it reflects a lack of magnitude. Consistent with this assumption, we found that when dimensions were used that did reflect assets of magnitude the left-anchoring effect did again replicate, whereas when the dimensions reflected a lack of magnitude, no laterality effect was observed at all[7]. When analysing Experiments 4a and b jointly, the corresponding interaction between group and side of dominant element, which was only a tendency in the two Experiments analysed separately, was significant, $F(1,17216.42) = 4.60$, $p = .03$, see Figures 3 and 4. We assume that lack of magnitude on the one hand (implying non-dominance), and primacy on the other hand, are not sufficiently congruent in meaning (see Casasanto, 2009) as to facilitate a conflation of metaphors. As a caveat however, it is possible that the above pattern was at least partly influenced by the fact that tasks requiring judgments at the marked end of a dimension are usually more difficult (Hines, 1990; Sherman, 1973, 1976; see also Discussion from Experiment 3). In this case, an existing left-anchoring effect in Group 2 (marked dimensions) could be masked by error variance. Speaking against this possibility, response latencies are not significantly longer in Group 2 (marked dimensions), which would be expected to be the case if indeed greater difficulty was a factor (see Hines, 1990).

The SDE replicated both in terms of accuracy and response time, whereas the left-anchoring effect was more consistently demonstrated for response times than for accuracies, in line with Experiments 2 and 3. According to the overall pattern of accuracies, working with the marked dimensions, from this point of view, again seems more difficult than working with the unmarked dimensions, which would be in line with the literature (Schriefers, 1990; Schubert, 2005; Sherman, 1973, 1976; Van der Schoot at al., 2009). This difference appears more pronounced for the genuinely more difficult pairs of narrower distance on the array, as compared to those of wider distance.

## Experiment 5: The Top-Anchoring Effect

The main argument of this paper is that a spatial component in the mental construction of ordered arrays can be identified once a few assumptions are made with respect to (a) the metaphoric use of the spatial dimension (see Experiment 4), and (b) the factor that determines the directional bias in the mental simulation of the dimension (see Experiments 1-4). With respect to this latter assumption, one further prediction can be made. If the directional bias (left-right) is determined by culturally acquired reading/writing habits, then analogous results should obtain in a vertical (top-bottom) setting, because reading/writing conventions in Western countries not only imply a proceeding from left to right, but also from top to bottom. The present experiment replicates Experiment 3, with response conditions both dominant and non-dominant, only using the vertical rather than the horizontal space.

## Method

### Participants

Forty undergraduate students from Cardiff University, School of Psychology (34 female, six male, mean age = 21.9 years) took part in the experiment, all with English-spoken backgrounds. They received course credit for their participation. They were randomly assigned to the two groups, such that there were 21 participants in Group 1, and 19 in Group 2. Four participants were discarded from further analyses because of low accuracies (two from Group 1, and two from Group 2). The final sample comprised 36 participants, 19 in Group 1 and 17 in Group 2.

### Materials and Procedure

All materials and procedures were the same as in Experiment 3, except that presentation on the screen was now vertical. That is, in the learning phase, for any stimulus pair ("A is *r* than B", or "B is *less r* than A") the part "is *r* than", or "is *less r* than", was presented on the central line of the screen, whereas the two names (A, B, respectively) were presented 7.5 cm above and 7.5 cm below the central line on the screen. Analogous to the left vs. right presentation mode in Experiment 3, each pair was presented with the dominant person once above, as in “A is *r* than B”, and once below the central line, as in “B is *less r* than A”, during learning.

In the test phase, Participants in Group 1 were asked to quickly and accurately identify the older, richer, taller, etc. person, whereas participants in Group 2 were asked to quickly and accurately identify the less old, less rich, less tall, etc., person in a pair. For testing, the two names were presented with a vertical 15 cm gap between them, centred around the central line of the screen (which was blank). For responding, participants used the arrow keys on the keyboard to indicate the respective direction (*up* with their left index finger vs. *down* with their right index finger). The experiment lasted between 30 and 40 minutes, including debriefing.

## Results

### Accuracy

The overall error level was 13.7%. The final linear mixed model had the following fixed factors: Group (dominant responding vs. non-dominant responding), pair distance (1step, ..., 4 steps), location of dominant element (top vs. bottom), and type of relation (*older*, …, *faster*). For the means see Table 4. Only the main effect for pair distance was significant, $\chi^2[df = 3] = 68.55$; $p < .0001$, replicating the SDE ($M_{1\ step} = .768$; $M_{2\ step} = .851$; $M_{3\ step} = .902$; $M_{4\ step} = .930$).

### Response latencies

After trimming, response latencies were analysed using a final model of the same type as above (for means see Table 4). Group 1 (dominant responding, $M_{dominant} = 1012$ ms) generated faster responses than Group 2 (non-dominant responding, $M_{non\text{-}dominant} = 1307$ ms), $F(1,34.18) = 7.44$, $p < .01$, and the pair distance effect replicated again, $F(3,6914.92) = 105.22$, $p < .0001$. Pairs of adjacent position on the hypothetical array ($M_{1\ step} = 1256$ ms) required more time to respond than pairs of wider distance ($M_{2\ step} = 1174$ *ms;* $M_{3\ step} = 1060$

*ms*; $M_{4\ step}$ = 970 ms). There was a significant effect of location of dominant element, $F(1,43.13) = 20.83$, $p < .0001$, showing a top-anchoring effect in the vertical dimension such that dominant elements presented at the top of the screen generated faster correct responses than dominant elements presented at the bottom ($M_{top}$ = 1081 ms, *vs.* $M_{bottom}$ = 1152 ms). This held when participants were searching for the dominant element as well as when they were searching for the non-dominant element, tested separately (Group 1: $F(1,24.00) = 11.82$, $p = .002$, *Cohen's d* = .17; Group 2: $F(1,19.55) = 9.01$, $p = .007$, *Cohen's d* = .15).

Average ordinal position of the pairs did play a role. First, a main effect, $F(1,6959.96) = 64.45$, $p < .0001$, indicated that responses were faster the closer a pair was located towards the maximum pole of the dimension (presumably the top location on participants' representation), $\beta = 47.00$. Second, the interaction with location of dominant element, $F(1,6932.29) = 37.54$, $p < .0001$, indicated that whilst pairs at an average ordinal position of 1.5 through 3.5 showed a top-advantage (responses being quicker when the dominant element was at the top), this advantage diminished across that range of ordinal positions, and was eventually reversed to a bottom advantage (responses quicker when the dominant element was at the bottom) for ordinal positions 4 and 4.5, $\beta = 35.68$. Post-hoc contrasts indicated that this numerical reversal was not significant at either of the two latter positions, both *t'*s < 1.98, both *p'*s > .14, whereas the top-advantage was significant at positions 1.5, 2, and 2.5, and 3, all *t*'s < -4.53, all *p*'s <.001 (Bonferroni-Holm corrected).

## Discussion

This experiment replicated the SDE for accuracies and response times in a vertical setting, and it also revealed a top-anchoring effect as a spatial response bias. Following our argument thus far, this supports the idea that, based on the prevalent reading/writing habits, primacy is not only conceived as moving from left to right, but also from top to bottom, which triggers spatial processes during the mental construction of an ordered dimension. This argument can be upheld for both groups, that is, for dominant as well as non-dominant responding. In other words, not only were participants faster to respond correctly when they were searching for more asset in magnitude and the dominant person was on top, they were also faster when they were searching for a lack of magnitude and the non-dominant person was at the bottom.

In line with the moderating effect of ordinal position on laterality effects reported by Shaki et al. (2012) and in the previous experiments, the top-anchoring effect in the latencies was reduced, and eventually even reversed, at ordinal positions closer to the non-dominant pole. Presumably, the impact of the dimensional layout (i.e., maximum=top) on reasoning is most pronounced when the reasoning is directed at elements close to the anchor (see Shaki et al., 2012). However, the reversal as such is not easily explained by the present account, based on primacy.

Experiment 6: The Role of Status and Power

As another issue to do with the materials selection so far, the dimensions used (*older, richer, taller, smarter, stronger, faster*) presumably incorporate connotations of status and/or power, as would their marked counterparts (*younger, poorer, shorter, dumber, weaker, slower*) of a lack of status and/or power. Schubert (2005, see also Giessner & Schubert, 2007) suggested that reasoning about social power might be supported by spatial processes such that high (vs. low) power connotations should be associated with elevated (vs. downwards oriented) levels on a vertical dimension (for an extension of these findings to status rank orders see von Hecker, Klauer, & Sankaran, 2013). Using spatial consistency effects similar to the present methodology, Schubert (2005) demonstrated that high power labels (e.g., “master”) were identified faster when presented higher as compared to lower in the perceptual field, and vice versa for low status labels (e.g., "servant"). In explaining this effect, Schubert (2005) argues for vertical embodiment: Higher means more powerful based on social perception (association between power and height in fighting animals), or developmentally based (children perceiving their parents or older siblings as taller and more powerful than themselves). This type of explanation is potentially applicable to the present Experiment 5, showing a top-anchoring effect in a vertical setting. In this experiment, participants were faster to correctly identify the *older, taller, richer* etc. person when they were searching for more asset in magnitude and the dominant person was on top as compared to when it was at the bottom. They were also faster to respond correctly when they were searching for a lack of magnitude and the non-dominant person was at the bottom as compared to when it was on top. It is possible that the processes identified by Schubert (2005) might have determined or co-determined these results. Therefore it appears important, at least when our argument is made with respect to a vertical setting, to use materials that do not have connotations of power and/or status. Experiment 6 therefore replicated Experiment 5 with materials that have no a priori association with power or status.

## Method

### Participants

Nineteen female undergraduate students from Cardiff University, School of Psychology (mean age = 19.2 years) took part in the experiment, all with English-spoken backgrounds. They received course credit for their participation. Ten participants were randomly assigned to Group 1 and nine to Group 2 (see below). Two participants were discarded from further analyses because of low accuracies (one from each group). The final sample comprised 17 participants, 9 in Group 1 and 8 in Group 2.

### Materials and Procedure

Procedures were the same as in Experiment 5 (vertical presentation), except that different materials were used. Participants were instructed that for all six experimental blocks, they had to learn rank orders among fictitious people who were wearing coloured jumpers. These jumpers should be imagined as being of a different colour, and the colour was always a mixed hue between either purple (Group 1) or green (Group 2) on the one hand, and a neutral grey on the other hand. Persons were to be compared in terms of one jumper's mixed hue being more of that colour than the other. In the learning phase, half of the pairs were presented as "A's jumper is *more purple/green* than B's", and the other half as "B's jumper is *less purple/green* than A's". In the test phase, participants were presented with vertically arranged pairs of names and had to decide which of the two persons would wear the jumper that was *more purple/green* than the other, by pressing either the up or down key on the keyboard. The experiment lasted between 30 and 40 minutes, including debriefing.

Results

Accuracy

The overall error level was 16.1%. The final model had the following fixed-effect structure: Group (purple vs. green), pair distance (1 step, ...,, 4 steps), location of dominant element (top vs. bottom), for the means see Table 5. Note that type of relation is dropped as a fixed factor in this experiment because each participant was only presented with one type of relation ("more" in terms of colour intensity). The effect of pair distance replicated again, $\chi^2[df = 3] = 91.15$; $p < .0001$, showing the SDE ($M_{1\ step} = .739$; $M_{2\ step} = .834$; $M_{3\ step} = .873$; $M_{4\ step} = .911$). No other significant effects occurred.

Response latencies

Correct response latencies were analysed using a final model with the same fixed effects structure as above for accuracies (for the means see Table 5). There was a main effect of pair distance, $F(3,12.89) = 10.49$, $p = .0009$, replicating the SDE ($M_{1\ step} = 1157$ ms; $M_{2\ step} = 1082$

ms; $M_{3\ step}$ = 991 ms; $M_{4\ step}$ = 909 ms). Location of dominant element was associated with a significant effect, $F(1,3254.21) = 11.91$, $p = .0006$, replicating the top-anchoring effect as seen in Experiment 5. Dominant elements presented on top generated faster correct responses than dominant elements presented at the bottom ($M_{top}$ = 1005 ms, *vs.* $M_{bottom}$ = 1065 ms), C*ohen's d* = .18[8]. Average ordinal position of pair had a significant main effect, $F(1,3256.60) = 99.49$, $p < .0001$, $\beta = 79.83$, as well as an interaction with location of dominant element, $F(1,3253.83) = 25.12$, $p < .0001$. Pairs at an average ordinal position of 1.5, 2, 2.5, 3, and 4 showed a diminishing top-advantage (responses being quicker when the dominant element was at the top), whereas pairs at ordinal positions 3.5 and 4.5 showed a bottom advantage (responses quicker when the dominant element was at the bottom), $\beta$ = 35.68. No other significant effects were obtained. Post-hoc contrasts indicated that the numerical reversal was significant at position 4.5, $t = 2.44$, $p = 0.04$, whereas the reversal was not significant at position 3.5, $t = 0.62$, $p = 0.53$. The contrasts at positions showing a top-advantage were significant at positions 1.5, 2, 2.5, and 3, all $t$'s > -3.374, all $p$'s < 0.003, whereas the top-advantage was not significant at position 4, $t = 1.34$, $p = 0.36$. All comparisons were Bonferroni-Holm corrected.

## Discussion

Hues of a colour mix between a definite colour (purple or green) and a neutral grey are different in terms of magnitude, i.e., hues close to the saturated colour representing "more" in terms of magnitude than hues close to the neutral grey. As such, these hues can have implications for dominance, but they are unlikely to have, per se, strong social psychological associations in terms of power or status. To the extent that we can accept differences in dimensional magnitude (as exemplified by colour hues) as independent of differences in social power and status, this experiment provides evidence that the results from Experiment 5 were presumably not entirely reducible to the mechanisms identified by Schubert (2005). In his work, Schubert (2005) argues in a genuinely social psychological way when interpreting his spatial consistency effects. Powerful labels, according to this approach, are identified faster when on top because of social psychological reasons for why one should mentally represent high power at the top of a perceived or imagined space. We acknowledge that this type of explanation is to some extent applicable to the results from Experiment 5, inasmuch as the comparative terms used in that study might have connotations of power or status. The present results however, obtained with coloured jumpers as stimuli, would require a different explanation. We submit that the top-anchoring effect observed here is due to people's tendency to construct a mental linear model of the rank order of colours by placing the most "colourful" item on top, and working downwards in construction. There is presumably a metaphorical blend between primacy as triggered by reading/writing habits (top-down), and magnitude on the dimension (an item being colour*ful* as opposed to colour*less*). Again, the impact of the dimensional layout (i.e., maximum = top) appeared most pronounced for elements close to the top anchor, with a tendency to reverse at the non-dominant end (see Shaki et al., 2012).

## Experiment 7a and 7b: The Role of Cultural Reading/Writing Habits

According to the present view, when mentally constructing an ordered sequence from piecemeal information about pairwise ranks, people tend to follow *primacy* as a semantic principle (via a metaphoric blending), and rely on their habitual reading/writing conventions to determine the direction of their construction. This latter assumption can best be addressed by collecting data from a population in which reading/writing conventions differ from those in the West, and preferably go from right to left for a clear juxtaposition with the majority of our European samples so far. The present experiment therefore replicated a basic version of

Experiment 3 (only dominant responding) in two samples with a Farsi background, the first from a University student population (7a), and the second from a non-university population with no, or very little, exposure to languages written from left to right (7b). Farsi is a language that is written from right to left. For the student sample, our predictions have to take into account that due to their academic backgrounds and aspirations, these participants would have had varied, but certainly considerable, exposure to Western international literature and websites for which knowledge in the left-right-oriented English language (or other left-right-oriented European languages) would be either a precondition or would accrue over time with practice. For this reason, the student sample cannot count as being *purely* of a right-left reading/writing background. However assuming that, at any rate, our participants would have had a considerable, if not fundamental, exposure to Farsi as well, we expected the left-anchoring effect to be substantially weakened if not reversed in comparison to the European samples, whilst the SDE should remain unchanged. For the non-university sample we predicted a clear reversal of the anchoring effect from left to right.

## Method

Participants

*7a, Student sample*. Twenty-six undergraduate students from Shahid Bahonar University of Kerman, Iran (25 female, one male, mean age = 21.0 years), took part in the experiment, all with mixed Farsi-English backgrounds. They received course credit for their participation. Six participants were discarded from further analyses because of low accuracies. The final sample comprised 20 participants.

*7b, Non-university sample*. Twenty-six individuals from Kerman, Iran, and surroundings, (13 female, 13 male, mean age = 34.8 years) volunteered to take part in the experiment without payment, all with literate Farsi background, who had no or very little exposure to left-right-oriented languages otherwise. Two participants were discarded from further analyses because of low accuracies. The final sample comprised 24 participants.

Materials and Procedure

*7a and 7b*. All materials and procedures followed Experiment 3, with materials translated into Farsi, and only using the dominant response modality, that is, participants were asked to identify the *older, richer, taller*, etc. person in a pair, exclusively. The experiment lasted between 30 and 40 minutes, including debriefing.

Results

Accuracy

*7a, Student sample*. The overall error level was 31.3%. We examined a final model with pair distance (1 step, ..., 4 steps) and side of dominant element (left vs. right) as fixed factors, for means see Table 6a. Pair distance showed a significant effect, $\chi^2[df = 3] = 35.59$; $p < .0001$, replicating the SDE ($M_{1\ step} = .629$; $M_{2\ step} = .677$; $M_{3\ step} = .710$; $M_{4\ step} = .733$). There were no other significant effects, in particular, there were no significant differences in accuracy between the two sides of the dominant element ($M_{left} = .684$, *vs.* $M_{right} = .690$), *Cohen's d* = .13.

*7b, Non-university sample*. The overall error level was 43.0%, across all participants and all test pairs. The final model had the same structure as in Experiment 7a (for the means see Table 6b). Pair distance showed a significant effect, $\chi^2[df = 3] = 12.09$; $p = .007$, replicating the SDE ($M_{1\ step} = .522$; $M_{2\ step} = .571$; $M_{3\ step} = .571$; $M_{4\ step} = .615$) but equal levels of accuracy between the second and third level. Side of dominant element was also significant, $\chi^2[df = 1] = 8.41$; $p = .004$, with responses being more correct when the dominant person was presented on the right as compared to the left side ($M_{left} = .550$, *vs.* $M_{right} = .589$), *Cohen's d* = .12. There were no further effects.

Response latencies

*7a, Student sample*. A final model with the same fixed effects structure as above was applied (for means, see Table 6a). There was a main effect of pair distance, $F(3,3105.13) = 13.68$, $p < .0001$, demonstrating faster correct responding at wider pair distances ($M_{1\ step}$ = 2069 ms; $M_{2\ step}$ = 2005 ms; $M_{3\ step}$ = 1904 ms; $M_{4\ step}$ = 1723 ms). No other effects were obtained. In particular, responding correctly when the dominant person was shown on the left side did not take less time than when the dominant person was shown on the right side ($M_{left}$ = 1897 ms, *vs.* $M_{right}$ = 1964 ms), *Cohen's d* = .06. Thus, neither in terms of accuracy nor response times was there any trace of a laterality effect in the student sample.

*7b, Non-university sample*. An analogous final model to the above was applied (for means see Table 6b), showing a significant effect of pair distance, $F(3,3251.15) = 9.17$, $p < .0001$, and demonstrating faster correct responding at wider pair distances (SDE). Pairs of adjacent position on the hypothetical array ($M_{1\ step}$ = 2232 ms) required more time to respond than pairs of wider distance ($M_{2\ step}$ = 2193 ms; $M_{3\ step}$ = 2019 ms; $M_{4\ step}$ = 1962 ms). Importantly, responding correctly when the dominant person was shown on the right side took less time than when the dominant person was shown on the left side ($M_{left}$ = 2177 ms, *vs.* $M_{right}$ = 2049 ms), *Cohen's d* = .09, although this effect was only visible as a tendency, $F(1,3251.29) = 2.30$, $p = .13$.

Neither sample showed any moderating influence of average ordinal position on the right-anchoring effect.

## Discussion

Accuracies were lower in this experiment than in the previous ones, and average response times were longer, especially in the non-university sample. This may reflect the circumstance that the participants from the student population at Kerman University and, most probably, those from the non-university population in Kerman were not as familiar with psychological experiments as the participants from the previous samples who presumably approached the situation with a higher degree of experience and routine.

In the student sample, the SDE but not the laterality effect replicated. As such, the absence of a laterality effect could be taken to mean that spatial processes might not play a sizeable role in explaining the data. It is, however, difficult to explain why spatial processes should have no effect on the Kerman student sample, a right-anchoring effect on the Kerman non-university sample, and a left-anchoring effect on the European samples without the present set of assumptions that assume spatial processing for all participants. According to the present rationale, students in Kerman have a strong cultural basis in Farsi, which would, as such, promote a right-anchoring effect for the type of experiment as used here. However, since these students, as part of their education at university, are also partly socialised in left-right reading/writing, particularly through their exposure to academic English which would support a left-anchoring effect, we submit that the two tendencies tended to cancel each other out in the present sample, leading to a null effect of side of dominant element.

On the other hand, the data from the non-university sample do show a clear reversal of the laterality effect observed in the European samples, although notably in terms of accuracies more clearly than in terms of response latencies. It is plausible that in a population (as in the present one) where accuracies are relatively low, there might be more hypothesis-related variance being expressed in the accuracies, rather than in a population (as in our Western European samples) that work on a high plateau of correctness anyway. The Iranian non-university participants found it more difficult to respond correctly, or make correct responses quickly, when the dominant person in a pair was presented left rather than right. Presumably, their acquired reading/writing habit (right-to-left) provided them with a direction for the construction of their mental models when they were learning the pairwise information. On this basis, metaphorical blending with primacy meant a tendency to place the most extreme person, representing the greatest asset of dimensional magnitude, to the right side in mental space.

Considering individual differences, it is plausible to assume that in both samples, but to different degrees, participants would show differential tendencies to left- or right-anchor their order dimensions. In the university sample, we observed 9 participants who were faster when the dominant element was on the left (on average: 374 ms). The remaining 11 participants showed the reverse tendency, that is, negative right-left differences (on average: 161 ms). On the other hand, in the non-university sample there were 10 participants for whom the difference was positive (on average: 60 ms) against 14 participants for whom it was negative (on average: 220 ms). From this juxtaposition one can see that both samples were mixed in that some participants were presumably constructing their dimensions from left to right, whereas others did it from right to left. However in the university sample the left-right constructions were more pronounced relative to the other direction, whereas in the non-university sample the right-left constructions seem relatively more pronounced, or distinct, than the left-right ones, considering the average time differences for responses.

The fact that participants with literate Farsi-English background (7a) exhibited no laterality effect whereas those with literate Farsi background without exposure to a left-to-right system (7b) did exhibit a clear right-anchoring effect is in line with research on numerical reasoning inasmuch as laterality effects appear cancelled in samples of participants with prior exposure to reading/writing habits in opposite directions. Thus, while numbers appear to be represented in increasing magnitude from left to right in English- and French-speakers, and from right to left in Arabic- and Farsi-speakers (Dehaene et al., 1993; Zebian, 2005), this pattern is weakened or cancelled for Farsi-French bilinguals, depending on the amount of exposure to the French left-to-right writing system (Fuhrman & Boroditsky, 2010; Dehaene et al., 1993). Also, Arabic-English biliterates showed a weakened right-to-left mental number line (Fuhrman & Boroditsky, 2010; Zebian, 2005). Interestingly, Shaki, Fischer, and Petrusic (2009) found left to right numerical SNARC effects in Canadians, but right to left SNARC-effects in Palestinians (who read and write Arabic form right to left), and no reliable spatial association for numbers in Israeli participants who might have been – as we speculate – most exposed to both directions of reading/writing.

## General Discussion

Although the existence of the SDE supports the notion that people construct analogue representations of rank orders, the effect per se does not provide a definitive demonstration that spatial processes are involved in such construction. Indeed, some of the existing theoretical accounts of the effect make that assumption whereas others do not (cf. Denis, 2008; Leth-Steensen & Marley, 2000). The strategy of the present research was to provide independent evidence for spatial processes in terms of robust laterality and verticality effects over and above the SDE. The main argument is that this particular pattern of effects is difficult to explain merely on the basis of an analogue representation as such, but would afford the additional assumption that space provides an analogue dimension onto which the relations between stimuli are projected. In earlier research it has been claimed that analogue, metaphoric connections between abstract concepts (such as the dimension on which a linear order is learnt) and the physical dimension of space lie at the heart of fundamental cognitive processes when dealing with abstract concepts (Barsalou, 1999, 2008; Boroditsky & Ramscar, 2002; Lakoff & Johnson, 1980). Metaphoric spatial effects have previously been obtained in areas such as the mental number line and the mental time line, mostly involving materials that incorporated some order information *a priori* (e.g., numbers, or months). The present research addresses effects obtained with materials that do not incorporate any *a priori* order information. For the materials used here, order needed to be established by mental construction in working memory (Brewer, 1987; Greeno, 1989).

Summary of results

To summarize the present results, the SDE replicated in seven consecutive experiments, confirming that this effect counts amongst the most robust and replicable effects in experimental psychology, in terms of both accuracy and response latency (e.g., Cohen Kadosh, Brodsky, Levin, & Henik, 2008; Leth-Steensen & Marley, 2000; Pohl & Schumacher, 1991; Sedek & von Hecker, 2004; von Hecker, Klauer & Sankaran, 2013). Further to this, the present research has shown that with learnt rank orders of five fictitious persons along abstract comparative dimensions (*older*, *richer, taller, smarter, stronger, faster*), Western participants were faster to identify the dominant person in a pair when that person was presented on the left or top of a computer screen rather than on the right or bottom (*left-anchoring*, *top-anchoring*, Experiments 1-6), with the horizontal effect reversing to a right anchoring in an Iranian sample with exclusive exposure to Farsi (Experiment 7). This type of effect was consistently observed in terms of response latency across the experiments, whereas only Experiments 4b (vertical) and 7b (horizontal) showed a corresponding effect for accuracies[9]. For response times, responding from the grammatically non-dominant perspective (*less r*) yielded the expected effect in the vertical setting, that is, the same effect as when responding at the dominant end (*more r*, Experiment 5) but not in the horizontal setting (Experiment 3). Perceptual triggers as conveyed by presentation mode, or, by the grammatical surface structure of the stimuli, were ruled out as explanations (Experiment 2). Experiments 1 and 2 also ruled out that inclusion of the end elements in the ordered array drive the target effects. The horizontal effect disappeared when marked versions of the dimensions were used implying a lack of a particular magnitude (*younger*, *poorer, shorter, dumber, weaker, slower,* Experiment 4a and 4b), and when an Iranian sample of students was used who had exposure to both Farsi and English for reading and writing (Experiment 7a). The vertical variety of the spatial effect also replicated when dimensions were used that did not imply differences in power or social status (colour hues of jumpers, Experiment 6).

Theoretical model

The SDE has been taken to suggest that orders may be represented spatially (Huttenlocher, 1968; Leth-Steensen & Marley, 2000), assuming in particular positional discriminability (Estes, Allmeyer, & Reder, 1976; Woocher, Glass, & Holyoak, 1978; Baranski & Petrusic, 1992) as a model for a potentially mediating mechanism. The assumption here is that the represented location of an element within a mental array can be described as a distribution around the true location. These locations will tend to overlap to a greater extent for elements at narrow distances than for elements at wider distances (Holyoak & Patterson, 1981), which directly leads to predicting the SDE, namely, greater accuracy and quicker responding for pairs of elements at wider as compared to narrower distances.

However, neither the SDE, nor other indicators such as end anchoring effects (Woocher, Glass, & Holyoak, 1978) are by themselves sufficient to uniquely support the idea of spatial processes being involved in the representation of abstract linear orderings (see Leth-Steensen & Marley, 2000). In this situation, the present research tries to make the argument that once a left-right bias can be identified to hold in such representations, and at the same time be connected with a plausible origin in motor action planning and spatial cognition (acquired reading/writing direction), this could be helpful in making a more compelling case for a genuine spatial characteristic associated with linear order representations. This is the main argument of the paper.

In particular, and in order to forge such an argument, we addressed two basic questions: (1) Is it possible to observe traces of the process by which the construction is triggered? Or, in other words, can one find traces of the information that the cognitive system may use to initiate a starting point and a direction within representational space, for construction? And (2), what is the nature of the content of what is being constructed; that is, what semantics is the constructive simulation based on?

In answering question (1) we see the reported left-anchoring and top-anchoring effects as suggesting that *culturally learned habits* of reading/writing determine starting point and direction, such that the construction of the mental model starts on the left/top and proceeds to the right/bottom within representational space, for people raised with Western reading/writing conventions. This was assumed on the basis of research on the number line and time line (Dehaene et al., 1993; Fuhrman & Boroditsky, 2010; Maass & Russo, 2003; Ouellet et al., 2010; Santiago et al, 2007; Tversky et al., 1991; Zebian, 2005), from which cultural specificity was observed in terms of left-to-right effects changing into right-to-left effects when switching from participant samples from Western countries to samples from Eastern countries with right-to-left reading/writing conventions. The idea that the starting point for simulation derives from the individually acquired reading/writing habit is further corroborated by earlier findings showing that literate adults spontaneously draw action sequences from left to right in an Italian sample, and from right to left in an Arabic sample (Maass & Russo, 2003), and that this kind of ordering bias is found absent in preliterate German- and Hebrew-speaking kindergarteners (Dobel et al., 2007). Our results from Experiment 4b (only centralized presentation in the learning phase, and horizontal testing) imply that the final layout of the mental representation (horizontally *or* vertically) may be determined only at test, as cued by context factors. However, what is predetermined during construction at learning may be just the constraint that the maximally dominant element of the order needs to be placed at the starting position (horizontal *or* vertical) within a two-dimensional reading/writing space as determined by cultural background.

With respect to question (2) we propose that the content of the simulated spatial dimension relates to *primacy*, whereby primacy is assumed to blend metaphorically with dominance, as it is often implied by the meaning of the dimensional magnitude (see Casasanto, 2009; Pecher, Van Dantzig, Boot, Zanolie, & Huber, 2010, for the blending argument). In support of this assumption we found in Experiment 4 that the left-anchoring effect disappeared when marked versions of the dimensions were used (*younger, poorer, shorter, dumber, weaker, slower*) whereas the same effect remained in force in the condition in which the unmarked versions were used. This pattern is predicted from the blending-with-dominance argument because the semantics of the marked versions (as given above) do not imply positive assets of magnitude in the same way as the unmarked versions do, and therefore, by lack of semantic congruity, the meanings of the marked terms are not assumed to easily blend with primacy. The unmarked terms, as we assume for the order terms we used here, reflect dominance in a more immediate way and therefore blend with primacy. Note that this affects only the issue of where to anchor the model. If an anchor is not easily to be found (marked terms), spatial construction can still unfold. However, it is likely that no consistent anchoring takes place so that anchoring will sometimes occur to the left and sometimes to the right. This by itself does not mean that people cannot respond to the task or construct a spatial mental model. They are assumed to do so, only the orientation of the constructed models will be more random and will not exhibit a consistent left-anchoring bias.

"Magnitude" is taken here to mean general quantity on any dimension (see Dehaene et al., 1993, 1998; Fias, Lammertyn, Reynvoet, Dupont, & Orban, 2003) which has to be distinguished from those particular semantics of magnitude that have power and status associations (Schubert, 2005). Whilst the majority of our experiments indeed used power/status-related materials, Experiment 6 addressed a more general notion of magnitude (still suitable to derive dominance relations between individual elements) and provided evidence for the same anchoring effect using materials that did not carry such associations. This supports the interpretation that the hypothetical process of a blending between primacy and dominance should be seen in terms of magnitudes in general (i.e., a general sense of *more of* as implying dominance, and being blended with a general sense of *taking priority*).

The empirical signature effect that we use to support our general argument is a lateral anchoring bias (left-to-right in Westerners, right-to-left in Iranians), which we explain as follows, *mutatis mutandis* for the vertical dimension (top-to-bottom). When learning about a number of relations reflecting a linear order between five persons, A..E, a (Western) participant will construct an analogue, spatial mental model much in the same way as the classical literature suggests (e.g., DeSoto et al., 1965; Huttenlocher, 1968; Potts, 1972, 1974; Leth-Steensen & Marley, 2000). As part of this reasoning (using transitivity and the shifting of elements as documented by the above research) the maximally dominant element (A) is identified, and, by virtue of the primacy notion as triggered by reading/writing habit, is placed to the *left*, as an anchor to start with. The model is then constructed in *rightward* direction. When later tested on any pair within the represented linear order, we assume that a participant will activate this representation, in particular, its spatial aspects. When the queried pair is visually presented such that the dominant person is on the *right*, the spatial (visual) input provided by such an arrangement would create interference with the pre-existing, linear mental model which would contain the rank order A – B – C – D – E with the element personifying the maximum amount of dimensional magnitude represented on the *left*. This interference would then slow down the participant's response as compared to a case when the mentally modelled, and the actual episodic, alignments of the dimension were of the same orientation in space. These arguments also receive support from the neurophysiological research on the SDE and linear order learning in general, most of which shows involvement of the same parietal areas that are also known to be involved in spatial processing in general

(Acuna et al., 2002; Christoff et al., 2001; Goel and Dolan, 2001; Heckers et al., 2004; Knauff, 2013; van Opstal et al., 2009). In the light of this basic theoretical view, the present results raise a number of issues that will be addressed in turn.

Spatial reasoning and mental representations

There are at least two distinct ways how people represent spatial information. The first has been thought to imply mental imagery, and as such to contain metric information (Logan, 1994), or prescribed points of view or perspectives (Finke & Shepard, 1986; Kosslyn, 1980). The second, more relevant here, is sometimes referred to as *conceptual representation* (Logan, 1994) or *categorical spatial relations representation* (Kosslyn, 1994). Referred to in this paper as *mental model*, this type of representation does not incorporate any particular image or visual perspective per se, but, in a more abstract, integrated way, contains the spatial interrelations between the cognitive entities involved, allowing for reorientation, multiple perspectives, and spatial inferences (Baird, 1979; Knauff, 2013; Rinck, Hähnel, Bower, & Glowalla, 1997; Tversky, 1993). This latter type of representation underlies, as we assume, the SDE and the laterality effects reported here. The literature on spatial mental model construction (Glenberg, Meyer, & Lindem, 1987; Hegarty & Just, 1993; Rinck et al., 1997; Zwaan & Radvansky, 1998) is primarily concerned with spatial content, the representation of which appears to be by an analogue dimension. For example, in story reading, response times are shown to be related to the distance between a protagonist whom the participant was focusing on, and the probed object in terms of the locations mentioned in the story (e.g., O'Brien & Albrecht, 1992; Wilson, Rinck, McNamara, Bower, & Morrow, 1993). In contrast, when explaining spatial components in an analogue representation that has involved the SDE in previous literature and in the experiments reported here, one is dealing with ranked instantiations of an abstract concept which is not necessarily spatial by content, such as, for example, *older* or *richer*. On the one hand, it is obvious that such abstract concepts may be linked to space by means of some concrete metaphor or way of linguistic expression. For example, concepts such as *socially powerful* vs. *powerless* carry a vertical connotation (see Schubert, 2005), as do evaluative concepts (Meier & Robinson, 2004). On the other hand, the link to space as evidenced in the present paper is of a different nature. As Experiment 6 shows, the top-anchoring effect also occurs in a situation in which there is no metaphor or linguistic expression that would connect the degree of *purple-ness* or *green-ness* to any particular point in space. Rather, we believe that the metaphoric link that does occur in this and in our remaining experiments is of a very general kind; that is, a metaphoric link that blends primacy (as associated with a starting point on top or on the left side) with general dimensional dominance/magnitude (*more of* vs. *less of*), whatever the content may be. It should be noted that the spatial effects reported here arose with a task that required the on-line construction of a rank order in working memory, rather than the processing of materials that would already entail order information *a priori*, such as in most of the studies on the number line (e.g., numbers) or the time line (e.g., names of months).

## Magnitude processing in the brain

This leads to general considerations about magnitude processing in the brain. Using materials similar to those used in the present paper, many authors have found brain activation in prefrontal and parietal cortex areas that are known to be involved in working memory performance, and which are thought to support spatial processing. Many of these studies used procedures of learning and reasoning on series of transitively ordered non-spatial stimuli (Acuna et al., 2002; Christoff et al., 2001; Goel and Dolan, 2001; Heckers et al., 2004; van Opstal et al., 2009). In particular, Hinton et al. (2010), who used arbitrary symbols and artificial "more than" vs. "less than" relations, found graded activation in the bilateral parietal areas, with pairs of wider distance being associated with less neural activation. Corresponding behavioural data in that study revealed that test queries related to wider distances were easier than queries related to narrower distances (SDE, for a similar result see Zalesak & Heckers, 2009), and in post-experimental interviews most participants indicated that they had tried to form a mental chain in order to solve the task. Again, this correspondence between physiological and behavioural data in replicating the SDE seems to suggest that reasoning in terms of mental models about non-spatial contents may be supported by spatial simulations, and by analogue cognitive processes as reflected in neural brain activity in those areas of the cortex that have been associated with spatial processing (for an integrative theory about how visual and non-visual spatial areas in the brain are involved in the construction of mental models and simulations, see Knauff, 2013).

Some authors have proposed that functions supported by the parietal lobe are related to a general simulation and magnitude comparison device (for example, Barsalou, 2008; Fias et al., 2003; Walsh, 2003, see also Dehaene et al., 1998), and others have argued that such a common mechanism would still not necessarily imply the existence of a common mental representation of magnitude (Cohen Kadosh et al., 2008). Without being able to provide a conclusive answer to this question yet, the present results do support the notion that spatial simulation effects are observable at the level of mental representation. One main argument for this stems from Experiment 2, showing that when there was no perceptual hint at spatially ordering the elements during learning, people with English-speaking backgrounds still exhibited left-anchoring spontaneously, which we think indicates construction of a spatial model with the maximum positioned on the left side. This bias, since not perceptually triggered, is presumably due to a mental orientation of the order dimension that is established during construction (simulation).

One may ask about the functional value of simulations like this in the context of behavior. At the most general level, we assume that the ecological benefit of a simulation like this is to facilitate responding (Niedenthal et al., 2005). Therefore, in the present case, the generation of a response must in some way be linked to orientation. Therefore again, it is reasonable to speculate that response generation functions via determining which of the two stimuli is "rightfully" assigned to the *left* (primacy bv virtue of reading/writing habit). Whatever needs to be "rightfully" assigned to the left, in a judgment situation, is decided from the evoked mental model (mental simulation). In the experimental context, interference may arise such that the presented order within a pair conflicts with the directional information as memorized, so the "reading off" of an answer is not directly possible because the knowledge source, i.e., the mental model, shows no directional congruence with the stimuli as presented, or, the stimuli cannot be immediately mapped onto this model. In order to generate a response, one has to either flip the item around mentally to achieve directional congruity, or mentally "acknowledge" the mismatch, logically calculate that in, and read off the answer from the model. In both cases, time delays are to be expected.

## Related concepts and explanations

*(1) Power/status as a vertical dimension.* Schubert (2005) proposed that social power is represented as a vertical dimension (Schubert, 2005; Giessner & Schubert, 2007), an argument that has recently been extended to social status (von Hecker et al., 2013). When asked to identify a stimulus associated with high power/status as "high power/status", location of display at the top leads to quicker responses than display at the bottom. Such findings are in line with theories of embodied cognition, positing that many perceptual and reasoning processes concerning abstract concepts, such as power and social status, are represented in terms of spatial features or dimensions (Barsalou, 1999; Boroditsky & Ramscar, 2002; Glenberg, 1997). It is possible and highly likely, given the evidence, that such direct metaphoric mappings between power/status and verticality do indeed exist, as reflected in language (e.g., *climbing* the career ladder, talking in a *condescending* way). However, in

Experiment 6 of the present series a top-anchoring effect analogue to those observed by Schubert (2005) did obtain despite the fact that no power or status information were implied in the materials. The explanation we give for the data reported here encompasses such materials as well, and it does not need the assumption of direct metaphoric mappings. Indeed, the present assumption is that of an *in*direct mapping of dimensional magnitude, irrespective of content: Whatever the magnitude denoted by the order dimension, *more of it* is metaphorically blended with *primacy* in a simulation process which itself unfolds in reading/writing direction.

*(2)* The literature on stimulus-response-compatibility has developed the concept of *polarity correspondence* (PC) in order to explain spatial mapping effects, mostly in binary classification tasks in which stimuli have to be classified into one of two response categories (for an overview see Proctor & Cho, 2006). The basic idea here is that the two conceptual alternatives in a given dimension (e.g., *old – young*) are coded as *plus* and *minus*, whereby the assignments of these codes typically follow the logic of linguistic markedness. For example, in *old – young*, the adjective *old* is *plus*-coded because it neutralizes to describe the dimension whereas *young* is *minus*-coded because it does not (Lakens, 2011). Spatial mapping effects are explained in the PC framework by assuming that not only stimuli, but also responses are *plus/minus*-coded; such that, for example an *up*-response key would be *plus*-coded as opposed to a *down*-key being *minus*-coded, as well as a *right*-response key being *plus*-coded as opposed to a *left*-response key being *minus*-coded (Proctor & Cho, 2006; Lakens, 2011). Responses should then meet interference and occur with longer latencies when stimulus-code and response-code are different as compared to when they are the same.

The type of explanation provided by the PC framework appears different from ours and does not cover the full extent of the present findings, despite similarity at the surface: Could it be possible that the left- and top-anchoring effects observed here were a result of the unmarked ends of the used dimensions, as well as left- and top-response options, being *plus*-coded, thus leading to quicker correct responses at such combinations as compared with other combinations where stimulus and response codes were different? This explanation is problematic. For all horizontal settings it would be unclear why, despite a wide agreement otherwise concerning *right*-responses being *plus*-coded (see Proctor & Cho, 2006), there should be a *plus*-coding for *left* responses in Westerners, but then again less so for Iranian participants (Experiment 7). This would require more *ad hoc* assumptions. The easier explanation in this case is that, according to the present framework, compatibility (or, lack thereof) exists not between two particular codes but between a) a spatial mental representation that was on-line constructed on the basis of previous rank order information, and b) a perceptual spatial input as actually provided at test, by the arrangement of stimuli on the screen. Also, according to the present view, the unmarked end of a dimension would not be invariably assigned a *plus*-code for all people, but would be placed at the procedural start location according to their respective reading/writing habits.

*(3) Magnitudes based on prior semantic knowledge.* The present experiments use short, arbitrary orderings, for which participant are presented with relational information (A > B, etc.). However recently, Chen et al. (2014) presented a model of comparative magnitude reasoning based on non-relational information. The model describes how magnitudes are formed in working memory based on computations over more basic features of the to-be-compared items (e.g., animals), as stored in long-term memory. The scope of the model is to explain how the SDE, semantic congruity effects and other signature effects of magnitude comparisons may arise, and how, in the first place, a comparative judgment about two stimuli on a magnitude dimension is generated on the basis of non-comparative information. The basis for the model is not spatial processing but Bayesian computation, and the magnitude codes it produces are not conceptualised as necessarily spatial. Empirically, some of the

standard effects (e.g., end-anchoring and more general serial position curves) are not found for such magnitude continua based on long-term memory contents. On the other hand, positional coding, and its associated effects, have long been associated with a genuinely spatial representation (Holyoak & Patterson, 1981). The question arises therefore to what extent LTM-based comparisons as represented by the Chen et al. (2014) model should be seen as supported by spatial processes in a similar way as we propose for short ad-hoc orders based on explicit relational information. In the present paper, the basic proposition is that a left-right laterality effect should be taken as a fundamental signature of the involvement of spatial processes. The question is therefore to be relegated to future empirical research: If laterality effects due to the presentation side of the dominant element in a comparison pair do arise for LTM-based comparisons, then this should be taken to indicate that spatial processes are involved in such representations. It is worth noting that the scope of the present paper is not, as it is for Chen et al. (2014), to explain how comparisons are generated out of non-comparative information. In contrast, our question arises at a later point. We assume that the comparisons are already given (in whichever way learned by the perceiver), and we are interested to see whether spatial characteristics of the ensuing mental representation can be identified.

## Implications for SNARC effects

The standard SNARC effect supports the idea of a number line that extends from left (small numbers) to right (large numbers, which reverses in cultures with right-left-systems for reading and writing (see Chatterjee, 2001; Dehaene, Bossini, & Giraux, 1993; Maass & Russo, 2003; Tversky, Kugelmass, & Winter, 1991; Zebian, 2005). We distinguish between *magnitude* and *primacy*, and we have argued throughout the paper that it is crucial for the semantics of the dimension to what extent the two can be blended. On the basis of prior research showing that left-to-right biases in social perception are related to perceptions of agency and action schemata (Fuhrman & Boroditsky, 2010; Maas & Russo, 2003; Maass, Suitner, Favaretto, & Cignacchi, 2009; Tversky, 1991) we assume that primacy is conceived in an action-theoretical way, meaning that the learned reading/writing habit basically provides a template and a starting point for action, in other words, for "what to do first". In our experiments, we believe that primacy in terms of starting an action is strongly associated with the notion of "first" in its most general form (meaning "supreme", "most substantial", "most important", etc.), such that a blending can occur between primacy in terms of an action sequence (Casasanto, 2009) and dominance as derived from the dimensional semantics. On this basis the directional orientation of the numerical SNARC effect can be explained, on an ad-hoc level, by assuming that the semantics of the number line are best described by "counting". In other words, once the reading/writing template scheme dictates to start on the left side, the unfolding action sequence itself comprises the counting from number 1 upwards in single units. Thus, the number 1 represents absolute dominance because it comes *first* in counting. The first step in counting dominates the second step in the same way as, in our materials, the older person dominates the less old. Since, as we believe, primacy is blended with dominance, the older person is represented to the left of the less old in the same way as the first counting result ("1") is represented to the left of the second counting result ("2"). It needs to be reiterated that according to our model, not magnitudes *per se* are simulated by the hypothetical dimension or line, but *primacy*; and due to a metaphoric blend between primacy and dominance, greater magnitudes (to the extent that they imply dominance) will be simulated to be on the left, and lesser magnitudes on the right. This generates different predictions for the present series of experiments as compared to the SNARC paradigm. In the present experiments, magnitude *does* imply dominance ("older" represents an asset in age, and therefore dominates the "less old"). In SNARC however, number magnitude *does not* imply dominance. Each counting step dominates the subsequent one because it is performed first, such that the number that is lesser in magnitude is, under our assumption, higher in dominance, leading to large numerical magnitudes being represented on the right, as the empirical SNARC findings show. It is also possible that primacy information in the number line is accessible without any blending with dominance, as it might be directly implied via the action schema of counting.

Shaki et al. (2012) found that when comparing magnitudes of animals shown side by side and responding on keys correspondingly with their left or right hand, English-speaking participants were quicker using their left hand (than their right) when choosing the larger animal out of a subset of relatively large animals, and quicker using their right hand when choosing the larger animal out of a subset of relatively small animals. Conversely, they were quicker using their left hand when choosing the smaller amongst small animals, and quicker using their right hand when choosing the smaller amongst large animals. The authors interpreted these findings as instruction-dependent, non-numerical SNARC-like effects in the RTs across the two forms of the comparative instructions (which stayed constant within an experimental block).

From the present view, we would agree that in Shaki et al.'s (2012) experiments, the anchoring of the mental model depends on instruction: In a "larger"-block the largest animal is placed on the left, whereas in a "smaller"-block, the smallest animal is placed on the left. We submit the following as explanation for these "ad hoc" anchorings. Different from our experiments, Shaki et al.'s (2012) design does not involve a learning phase in which all pairs are presented before testing begins. We believe that in our experiments, this learning phase is actually the phase in which the mental model is constructed; if there is no such phase, anchoring has to use the available instructional label ("larger" or "smaller") as constraint for ad-hoc construction: either the smallest or largest animal will be placed on the left. According to our view, if left unconstraint, Western people will (with our materials) spontaneously construct their model by placing that element on the left which is dominant in terms of dimensional asset, that is, the oldest, tallest, fastest, etc. When using marked terms (words describing a lack of dimensional asset), we believe that this process is more difficult and not so easily triggered. In summary, the difference between ours and Shaki et al.'s (2012) experimental setting is this: In their experiments, the dimensional asset (magnitude) of size is not very salient overall, because pairs were not presented for learning. When being tested, participants use the instruction for ad-hoc anchoring their dimension, whereby they place the smallest animal on the left when "smaller" is asked for, and the largest animal on the left when "larger" is asked for. In our experiments in contrast, the learning phase makes the dimensional magnitude as such salient and enables the participant to spontaneously place the most dominant element on the left (blending with primacy). Therefore we see left-anchoring consistently, amongst our Western participants.

In the majority of our experiments, we did observe an interaction between side of dominant element and average ordinal position of the pair. These effects, we think, are germane to Shaki et al.'s (2012). Our findings show that the closer a pair is to the maximum dominant pole of the dimension, the more pronounced the left-anchoring effect turns out. The further an ordinal position moves away from this maximum pole, the more the left-side facilitation is being washed out. Notably, we do not, in our horizontal experiments, replicate Shaki et al.'s (2012) conversion of a left-side- into a right-side-facilitation. However, we do observe a tendency of an analogous conversion of the top- into a bottom-facilitation in our experiments using the vertical dimension (see Experiments 5 and 6). We interpret all of these effects, similar to Shaki et al.'s (2012) interpretation, as testifying to the spatial character of the constructed dimension.

## Conclusion

In one of the seminal papers on the SDE, Moyer and Bayer (1976) suggested that "people perform certain reasoning tasks by ordering to-be-compared items along an imaginary axis in mental space" (p. 237). The contribution of the present research is to provide evidence beyond the SDE per se, for what may be spatial processes associated with, or in the service of, such reasoning that brings about the SDE. Whilst the SDE per se can be modelled and explained without spatial assumptions (Leth-Steensen & Marley, 2000), early anecdotal evidence (e.g., Huttenlocher, 1968) and our own results give support to the idea that spatial processes are indeed at work when people construct mental representations of transitive orders. The tool we used is a directional bias, and the idea of such a bias arising independent of the SDE is germane to recent research claiming distinct processes for quantity comparisons on a mental dimension (as related to the SDE), and for the specific order and direction that elements on that dimension are arranged into (Turconi, Campbell, & Seron, 2006). Our general assumptions are in line with neurophysiological research that locates cognitive functions relevant to spatial processing, magnitude processing, and transitive reasoning processes including some associated with SDE effects in one and the same structure (e.g., parietal lobe, intraparietal sulcus, see Hinton et al., 2010; Zalesak & Heckers, 2009). Mental space appears to be a general device that can help with, or mediate, reasoning about abstract concepts and dimensions (Boroditsky & Ramscar, 2002; Knauff, 2013). From this perspective, it is not surprising to find that in terms of simulation (Barsalou, 2008; Niedenthal et al., 2005), the mental construction of abstract dimensions appears to follow an individually acquired, outstanding, and paradigmatic connection between abstract ideas and space: the learned reading/writing technique. With respect to semantic content, the present findings suggest that the simulated dimension derives its meaning from a metaphorical blend between primacy and dominance, as derived from dimensional magnitude.

References

Acuna, B. D., Eliassen, J. C., Donoghue, J. P., & Sanes, J. N. (2002). Frontal and parietal lobe activation during transitive inference in humans. *Cerebral Cortex 12,*1312–1321.

Baird, J. (1979). Studies of the cognitive representation of spatial relations: I. Overview. *Journal of Experimental Psychology: General, 108,* 90-91.

Barsalou, L. W. (1999). Perceptions of perceptual symbols. *Behavioral and Brain Sciences, 22,* 637-660.

Barsalou, L. W. (2008). Grounded cognition. *Annual Review of Psychology, 59,* 617-645.

Banks, W. P. (1977). Encoding and processing of symbolic information in comparative judgments. In G. H. Bower (Ed.), *The psychology of learning and motivation* (Vol. 11, pp. 101-159). New York: Academic Press.

Baranski, J. V., & Petrusic, W. M. (1992). The discriminability of remembered magnitudes. *Memory & Cognition, 20,* 254-270.

Barclay, J. R. (1973). The role of comprehension in remembering sentences. *Cognitive Psychology, 4,* 229-254.

Barsalou, L. W. (1999). Perceptual symbol systems. *Behavioral and Brain Sciences, 22,* 577–609.

Barsalou, L. W. (2008). Cognitive and neural contributions to understanding the conceptual system. *Current Directions in Psychological Science, 17,* 91-95.

Bates, D., Maechler, M., Bolker, B. M., & Walker, S. (2015). "Fitting Linear Mixed-Effects Models using lme4." ArXiv e-print; in press, *Journal of Statistical Software,* http://arxiv.org/abs/1406.5823.

Boroditsky, L., & Ramscar, M. (2002). The roles of body and mind in abstract thought. *Psychological Science, 13,* 185-189.

Brewer, W. F. (1987). Schemas versus mental models in human memory. In P. Morris (Ed.), *Modelling cognition* (pp. 187–197). Chichester, England: Wiley.

Casasanto, D. (2009). Embodiment of abstract concepts: Good and bad in right- and left-handers. *Journal of Experimental Psychology: General, 138,* 351-367.

Chatterjee, A. (2001). Language and space: Some interactions. *Trends in Cognitive Science, 5,* 55–61.

Chen, D., Lu, H., & Holyoak, K. J. (2014). The discovery and comparison of symbolic magnitudes. *Cognitive Psychology, 71,* 27-54.

Christoff, K., Prabhakaran, V., Dorfman, J., Zhao, Z., Kroger, J.K., Holyoak, K.J., et al. (2001). Rostrolateral prefrontal cortex involvement in relational integration during reasoning. Neuroimage 14, 1136–1149.

Clark-Carter, D. (2004). *Quantitative psychological research: A student's handbook.* New York: Psychology Press.

Cohen Kadosh, R., Brodsky, W., Levin, M., & Henik, A. (2008). Mental representation: What can pitch tell us about the distance effect? *Cortex, 44,* 470-477.

Dehaene, S., Bossini, S., & Giraux, P. (1993). The mental representation of parity and number magnitude. *Journal of Experimental Psychology: General, 122,* 371–396.

Dehaene, S., Dehaene-Lambertz, G., & Cohen, L. (1998). Abstract representations of numbers in the animal and human brain. *Trends in Neurosciences, 21,* 355–361.

Denis, M. (2008). Assessing the symbolic distance effect in mental images constructed from verbal descriptions: A study of individual differences in the mental comparison of distances. *Acta Psychologica, 127,* 197-210.

De Soto, C. B., London, M., & Handel, S. (1965). Social reasoning and spatial paralogic. *Journal of Personality and Social Psychology, 2,* 513-521.

Dobel, C., Diesendruck, G., & Bölte, J. (2007). How writing system and age influence spatial representations of actions: A developmental, cross-linguistic study. *Psychological Science, 18,* 487–491.

Estes, W. K., Allmeyer, D. J., & Reder, S. M. (1976). Serial position functions for letter identification at brief and extended exposure durations. *Perception & Psychophysics, 19,* 1-15.

Fias, W., Lammertyn, J., Reynvoet, B., Dupont, P., & Orban, G. (2003). Parietal representation of symbolic and nonsymbolic magnitude. *Journal of Cognitive Neuroscience, 15,* 47-56.

Finke, R. A., & Shepard, R. N. (1986). Visual functions of mental imagery. In: K. R. Boff, L. Kaufman, & J. P. Thomas (Eds.), *Handbook of perception and human performance* (pp. 37-1 to 37-55). New York: Wiley.

Fuhrman, O., & Boroditsky, L. (2010). Cross-cultural differences in mental representations of time: Evidence from an implicit nonlinguistic task. *Cognitive Science, 34,* 1430-1451.

Gevers, W., Reynvoet, B., & Fias, W. (2003). The mental representation of ordinal sequences is spatially organized. *Cognition, 87,* B87-B95.

Gevers, W., Caessens, B., & Fias, W. (2005). Towards a common processing architecture underlying Simon and SNARC effects. *European Journal of Cognitive Psychology, 17,* 659–673.

Giessner, S. R., & Schubert, T. W. (2007). High in the hierarchy: How vertical location and judgments of leaders' power are interrelated. *Organizational Behavior and Human Decision Processes, 104,* 30-44.

Glenberg, A.M., Meyer, M., & Lindem, K. (1987). Mental models contribute to foregrounding during text comprehension. *Journal of Memory and Language, 26,* 69-83.

Glenberg, A. M. (1997). What memory is for. *Behavioral and Brain Sciences, 20,* 1–55.

Goel, V., Dolan, R. J. (2001). Functional neuroanatomy of three-term relational reasoning. *Neuropsychologia, 39,* 901–909.

Greeno, J. G. (1989). Situations, mental models, and generative knowledge. In D. Klahr & K. Kotovsky (Eds.), *Complex information processing* (pp. 285–318). Hillsdale, NJ: Erlbaum.

Hamilton, H. W., & Deese, J. (1971). Does linguistic marking have a psychological correlate? *Journal of Verbal Learning and Verbal Behavior, 10,* 707-714.

Heckers, S., Zalesak, M., Weiss, A. P., Ditman, T., & Titone, D. (2004). Hippocampal activation during transitive inference in humans. *Hippocampus, 14,* 153–162.

Hegarty, M., & Just, M. A. (1993). Constructing mental models of machines from text and diagrams. *Journal of Memory and Language, 32,* 717-742.

Hegarty, M. (2004). Mechanical reasoning by mental simulation. *Trends in Cognitive Sciences, 8,* 280–285.

Hines, T. M. (1990). An odd effect: Lengthened reaction times for judgments about odd digits. *Memory and Cognition, 18*, 40-46.

Hinton, E. C., Dymond, S, von Hecker, U. & Evans, C. J. (2010). Neural correlates of relational reasoning and the symbolic distance effect: Involvement of parietal cortex. *Neuroscience, 168,* 138-148.

Holyoak, K. J., & Patterson, K. K. (1981). A positional discriminability model of linear-order judgments. *Journal of Experimental Psychology: Human Perception and Performance, 7,* 1283-1302.

Hommel, B., Müsseler, J., Aschersleben, G., & Prinz, W. (2001). The theory of event coding (TEC): A framework for perception and action planning. *Behavioral & Brain Sciences, 24,* 849–878.

Huttenlocher, J. (1968). Constructing spatial images: A strategy in reasoning. *Psychological Review, 75*, 550-560.

Jaeger, T. F. (2008). Categorical data analysis: Away from ANOVAs (transformation or not) and towards logit mixed models. *Journal of Memory and Language, 59,* 434-446.

Judd, C. M., Westfall, J., & Kenny D. A. (2012). Treating stimuli as a random factor in social psychology: A new and comprehensive solution to a pervasive but largely ignored problema. *Journal of Personality and Social Psychology, 103,* 54-69.

Knauff, M. (2013). *Space to reason. A spatial theory of human thought.* Cambridge, MA: MIT Press.

Kosslyn, S. M. (1980). *Image and mind.* Cambridge, MA: Harvard University Press.

Kosslyn, S. M. (1994). Im*age and brain: The resolution of the imagery debate.* Cambridge, MA: MIT Press.

Lakens, D. (2011). Polarity correspondence in metaphor congruency effects: Structural overlap predicts categorization times for bipolar concepts presented in vertical space. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 38,* 726-736.

Lakens, D., Schneider, I. K., Jostmann, N. B., & Schubert, T. W. (2011). Telling things apart: The distance between response keys influences categorization times. *Psychological Science, 22,* 887-890. DOI:10.1177/0956797611412391

Lakoff, G., & Johnson, M. (1980). *Metaphors we live by*. University of Chicago Press.

Leth-Steensen, C., & Marley, A. A. J. (2000). A model of response time effect in symbolic comparison. *Psychological Review, 107*, 62–100.

Logan, G. D. (1994). Spatial attention and the apprehension of spatial relations. *Journal of Experimental Psychology: Human Perception and Performance, 20,* 1015–1036.

Maass, A., & Russo, A. (2003). Directional bias in the mental representation of spatial events: Nature or culture? *Psychological Science, 14,* 296–301.

Maas, A., Suitner, C., Favaretto, X., & Cignacchi, M. (2009). Groups in space: Stereotypes and the spatial agency bias. *Journal of Experimental Social Psychology, 45,* 496-504.

Marks, D. F. (1972). Relative judgment: A phenomenon and a theory. *Perception & `Psychophysics, 11,* 156-160.

Meier, B. P., & Robinson, M. D. (2004). Why the sunny side is up. *Psychological Science, 15,* 243-247.

Moyer, R. S., & Bayer, R. H. (1976). Mental comparison and the symbolic distance effect. *Cognitive Psychology, 8,* 228-246.

Moyer, R. S., & Dumais, S. T. (1978). Mental comparison. In G. H. Bower (Ed.), *The psychology of learning and motivation* (Vol. 12, pp. 117-155). New York: Academic Press.

Niedenthal, P., Barsalou, L. W., Winkielman, P., Krauth-Gruber, S., & Ric, F. (2005). Embodiment in attitudes, social perception, and emotion. *Personality and Social Psychology, Review, 9,* 184-211.

O'Brien, J. E., &Albrecht, E. J. (1992). Comprehension strategies in the development of a mental model. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 18,* 777-784.

Ouellet, M., Santiago, J., Funes, M. J., & Lupianez, J. (2010). Thinking About the Future Moves Attention to the Right. *Journal of Experimental Psychology-Human Perception and Performance, 36*(1), 17-24. doi: 10.1037/a0017176

Pecher, D., Van Dantzig, S., Boot, I., Zanolie, K., & Huber, D. E. (2010). Congruency between word position and meaning is caused by task-induced spatial attention. *Frontiers in Psychology, 1,* 30.

Pohl, R., & Schumacher, S. (1991). Handlungssequenzen und Wortlisten als hierarchische lineare Ordnungen: Einflüsse auf den Distanzeffekt [Action sequences and word lists as hierarchical linear orderings: Influences on the distance effect]. *Zeitschrift für experimentelle und angewandte Psychologie, 38,* 43–62.

Potts, G. R. (1972). Information processes used in the encoding of linear orderings. *Journal of Verbal Learning and Verbal Behaviour, 11,* 727-740.

Potts, G. R. (1974). Storing and retrieving information about ordered relationships. *Journal of Experimental Psychology, 103,* 431–439.

Proctor, R. W., & Cho, Y. S. (2006). Polarity correspondence: A general principle for performance of speeded binary classification tasks. *Psychological Bulletin, 132,* 416-442.

R Core Team (2013). *R: A language and environment for statistical computing.* R Foundation for Statistical Computing, Vienna, Austria. URL http://www.R-project.org/.

Riley, C. A. (1976). The representation of comparative relations and the transitive inference task. *Journal of Experimental Child Psychology, 22,* 1-22.

Rinck, M., Hähnel, A., Bower, G.H., & Glowalla, U. (1997). The metrics of spatial situation models. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 23,* 622-637.

Santiago, J., Lupianez, J., Perez, E., & Funes, M. J. (2007). Time (also) flies from left to right. *Psychonomic Bulletin & Review,* 14, 512–516.

Schriefers, H. (1990). Lexical and conceptual factors in the naming of relations. *Cognitive Psychology, 22,* 111-142.

Schubert, T. (2005). Your Highness: Vertical Positions as Perceptual Symbols of Power. *Journal of Personality and Social Psychology, 89,* 1-21.

Sedek, G., & von Hecker, U. (2004). Effects of subclinical depression and aging on generative reasoning about linear orders: Same or different processing limitations? *Journal of Experimental Psychology: General, 133,* 237-260.

Shaki, S., Fischer, M. H., & Petrusic, W. M. (2009). Reading habits for both words and numbers contribute to the SNARC effect. *Psychonomic Bulletin and Review, 16,* 328-331.

Shaki, S., Petrusic, W. M., & Leth-Steensen, C. (2012). SNARC effects with numerical and non-numerical symbolic comparative judgments: Instructional and cultural dependencies. *Journal of Experimental Psychology: Human Perception and Performance, 38,* 515-530.

Sherman, M. (1973). Bound to be easier? The negative prefix and sentence comprehension. *Journal of Verbal Learning and Verbal Behavior, 12*, 76-84.

Sherman, M. (1976). Adjectival negation and the comprehension of multiply negated sentences. *Journal of Verbal Learning and Verbal Behavior, 15,* 143-157.

Singmann, H., & Bolker, M. (2014). afex: Analysis of Factorial Experiments. *R package version* 0.12–135.

Smith, K. H., & Foos, P. W. (1975). Effect of presentation order on the construction of linear orders. *Memory and Cognition, 3,* 614–618.

Trabasso, T. R., Riley, C. A., & Wilson, E. G. (1975). The representation of linear order and spatial strategies in reasoning: A developmental study. In R. Falmagne (Ed.), *Reasoning: Representation and process* (pp. 201-229). Hillsdale, NJ: Erlbaum.

Turconi, E., Campbell, J. I. D., & Seron, X. (2006). Numerical order and quantity processing in number comparison. *Cognition, 98,* 273-285.

Tversky, B. (1993). Cognitive maps, cognitive collages, and spatial mental models. In A. U. Frank, & Campari, I. (Eds.), *Spatial information theory: A theoretical basis for GIS, Proceedings COSIT '93. Lecture notes in Computer Science,* 716 (pp. 14-24). Berlin: Springer.

Tversky, B., Kugelmass, S., & Winter, A. (1991). Cross-cultural and developmental trends in graphic productions. *Cognitive Psychology, 23,* 515–557.

Van der Schoot, M., Bakker Arkema, A. H., Horsley, T. M., & van Lieshout, E. C. D. M. (2009). The consistency effect depends on markedness in less successful but not successful problem solvers: An eye movement study in primary school children. *Contemporary Educational Psychology, 34,* 58-66.

Van Opstal, F., Fias, W., Peigneux, P., & Verguts, T. (2009). The neural representation of extensively trained ordered sequences. *Neuroimage, 47,* 367–275.

Von Hecker, U., Klauer, K. C., & Sankaran, S. (2013). Embodiment of social status: Verticality effects in multi-level rank-orders. *Social Cognition, 31,* 387-402.

Walsh V. (2003). A theory of magnitude: common cortical metrics of time, space and quantity. *Trends in Cognitive Sciences, 7,* 483–488.

Wilson, S. G., Rinck, M., McNamara, T. P., Bower, G. H., & Morrow, D. G. (1993). Mental models and narrative comprehension: Some qualifications. *Journal of Memory and Language, 32,* 141 - 154.

Woocher, F. D., Glass, A. L., & Holyoak, K. J. (1978). Positional discriminability in linear orderings. *Memory & Cognition, 6,* 165-173.

Zalesak, M., |& Heckers, S. (2009). The role of the hippocampus in transitive inference. *Psychiatry Research, 172,* 24–30.

Zebian, S. (2005). Linkages between number concepts, spatial thinking and directionality of writing: the SNARC effect and the REVERSE SNARC effect in English and in Arabic monoliterates, biliterates and illiterate Arabic speakers. *Journal of Cognition and Culture. Special Issue: on Psychological and Cognitive Foundations of Religiosity, 5,* 165-190.

Zwaan, R. A., & Radvansky, G. A. (1998). Situation models in language comprehension and memory. *Psychological Bulletin, 123,* 162-185.

Footnotes

1

Cohen's d was calculated in the classical way as the difference between the two means divided by the pooled standard deviation of the subsets of data under comparison.

2

Similar analyses excluding both extreme elements were conducted for all other experiments (2-7). The various predicted laterality effects were significant in Experiment 2, $p = .002$, but insignificant, or only at the level of tendencies, in the remaining cases. Note however that by excluding the end elements, 70% of the trials are excluded which reduced the test power considerably.

3

We also tested the possibility that within Group 2 (non-dominant responding) this result might have been due to a tendency for the side of dominant element effect to be reversing across ordinal pair positions, that is, a disordinal interaction between ordinal position and side of dominant element. However, the interaction between these two factors, when analysed separately for Group 2, was insignificant, $F(1,3523.61) = 0.32$, $p = .57$.

4

An adjective can be defined as unmarked when it neutralizes to describe the dimension, and as marked when it does not (Proctor & Cho, 2006). In the present context, *older, richer, taller, smarter, stronger,* and *faster* are used, each of which would, in its non-comparative form, describe the dimension in a neutral way, as opposed to their marked counterparts *younger, poorer, shorter, dumber, weaker,* and *slower*, which do not. Hamilton and Deese (1971) demonstrated that people are reliably able to distinguish these two types of adjectives.

5

Note that display direction is always completely confounded with response hand (e.g., left responses are necessitated for grammatically dominant responding when the dominant item is presented on the left where, conversely, right responses are necessitated for grammatically non-dominant responding when the dominant item is presented on the left). Given this point, it actually is quite meaningful that a performance advantage for dominant items on the left was found for grammatically dominant responding (in Expt. 1-4) and not for grammatically non-dominant responding (in Expt. 3) in spite of the well-known tendency for right-hand responding to be faster. We would like to thank one of the reviewers for pointing this out to us.

6

We thank an anonymous reviewer for sharing this idea with us.

7

We are aware of the fact that the support for this assumption is only indirect because by the methodology used, we do not directly observe the blend as such, but only its consequences, although those consequences were predicted. At any rate, it still leaves the possibility that those consequences might be caused by something else such as by chance and/or by a confound. The observed pattern is however consistent with the assumption, and potentially supportive of it.

8

This effect proved significant when testing the "green jumper" group separately ($p$=.03, $n$=9), but not when testing the "purple jumper" group separately ($p$=0.20, $n$=10), with case numbers being quite low for these comparisons.

9

This is in line with results on spatial consistency effects in the area of metaphorical embodiment of power and status, where similar effects are more consistently observed for response latencies than for accuracies (Schubert, 2005; von Hecker et al., 2013).

Table 1 Experiment 2, Accuracies and Response latencies by Display direction for dominant person, and Pair distance.

| Group 1 | Dominant person | Pair distance: 1 step | | 2 step | | 3 steps | | 4 steps | |
|---|---|---|---|---|---|---|---|---|---|
| Accuracy | left | .796 | (.121) | .895 | (.101) | .914 | (.081) | .916 | (.099) |
| | right | .730 | (.131) | .865 | (.114) | .898 | (.106) | .926 | (.142) |
| Latency | left | 801 | (346) | 741 | (423) | 618 | (388) | 496 | (413) |
| | right | 870 | (401) | 762 | (367) | 695 | (396) | 581 | (409) |
| **Group 2** | | | | | | | | | |
| Accuracy | left | .701 | (.146) | .793 | (.138) | .813 | (.196) | .890 | (.178) |
| | right | .709 | (.097) | .789 | (.113) | .824 | (.129) | .894 | (.103) |
| Latency | left | 991 | (620) | 895 | (600) | 809 | (606) | 748 | (717) |
| | right | 988 | (585) | 945 | (701) | 797 | (527) | 721 | (791) |
| **Group 3** | | | | | | | | | |
| Accuracy | left | .755 | (.124) | .837 | (.120) | .861 | (.158) | .901 | (.127) |
| | right | .738 | (.116) | .827 | (.114) | .848 | (.116) | .893 | (.126) |
| Latency | left | 763 | (352) | 710 | (361) | 618 | (437) | 478 | (372) |
| | right | 834 | (383) | 731 | (387) | 632 | (359) | 571 | (448) |

*Note*. Accuracies are given in proportion of correct responses. Response latencies are given in milliseconds. Standard deviations are presented in brackets.
Group 1: Left-dominant learning
Group 2: Right-dominant learning
Group 3: Half/half left- and right-dominant learning

<u>Table 2</u> Experiment 3, Accuracies and Response latencies by Display direction for dominant person, and Pair distance.

| Group 1 | Dominant person | Pair distance 1 step | | 2 step | | 3 steps | | 4 steps | |
|---|---|---|---|---|---|---|---|---|---|
| Accuracy | left | .794 | (.102) | .874 | (.119) | .906 | (.085) | .917 | (.104) |
| | right | .761 | (.103) | .855 | (.108) | .893 | (.110) | .962 | (.068) |
| Latency | left | 989 | (286) | 890 | (278) | 800 | (310) | 655 | (282) |
| | right | 1017 | (297) | 966 | (327) | 866 | (350) | 764 | (388) |
| **Group 2** | | | | | | | | | |
| Accuracy | left | .725 | (.106) | .790 | (.128) | .854 | (.132) | .904 | (.105) |
| | right | .719 | (.121) | .795 | (.139) | .833 | (.141) | .883 | (.151) |
| Latency | left | 1216 | (482) | 1171 | (535) | 1067 | (532) | 876 | (539) |
| | right | 1235 | (482) | 1164 | (487) | 1079 | (568) | 905 | (522) |

*Note*. Accuracies are given in proportion of correct responses. Response latencies are given in milliseconds. Standard deviations are presented in brackets.
Group 1: Dominant responding; Group 2: Non-dominant responding.

Table 3a Experiment 4a, Accuracies and Response latencies by Display direction for dominant person, and Pair distance.

| Group 1 | Dominant person | Pair distance: 1 step | | 2 step | | 3 steps | | 4 steps | |
|---|---|---|---|---|---|---|---|---|---|
| Accuracy | left | .839 | (.078) | .925 | (.044) | .948 | (.051) | .961 | (.093) |
| | right | .819 | (.079) | .897 | (.066) | .945 | (.057) | .942 | (.071) |
| Latency | left | 1499 | (728) | 1384 | (697) | 1151 | (649) | 1018 | (803) |
| | right | 1560 | (750) | 1454 | (779) | 1249 | (725) | 1124 | (843) |
| **Group 2** | | | | | | | | | |
| Accuracy | left | .733 | (.128) | .809 | (.155) | .825 | (.142) | .906 | (.125) |
| | right | .722 | (.126) | .812 | (.123) | .845 | (.119) | .906 | (.085) |
| Latency | left | 1465 | (740) | 1407 | (762) | 1199 | (687) | 1133 | (848) |
| | right | 1449 | (761) | 1381 | (746) | 1293 | (788) | 1108 | (750) |

*Note*. Accuracies are given in proportion of correct responses. Response latencies are given in milliseconds. Standard deviations are presented in brackets.
Group 1: Unmarked order dimension; Group 2: Marked order dimension.

<u>Table 3b</u> Experiment 4b, Accuracies and Response latencies by Display direction for dominant person, and Pair distance.

| Group 1 | Dominant person | Pair distance: 1 step | | 2 step | | 3 steps | | 4 steps | |
|---|---|---|---|---|---|---|---|---|---|
| Accuracy | left | .754 | (.123) | .828 | (.135) | .884 | (.102) | .909 | (.148) |
| | right | .723 | (.130) | .813 | (.143) | .839 | (.166) | .876 | (.161) |
| Latency | left | 1070 | (658) | 943 | (525) | 831 | (510) | 705 | (646) |
| | right | 1100 | (623) | 961 | (488) | 877 | (585) | 815 | (705) |
| **Group 2** | | | | | | | | | |
| Accuracy | left | .751 | (.123) | .810 | (.120) | .853 | (.144) | .902 | (.116) |
| | right | .730 | (.156) | .803 | (.171) | .856 | (.112) | .855 | (.159) |
| Latency | left | 1132 | (569) | 1033 | (587) | 949 | (711) | 836 | (698) |
| | right | 1139 | (589) | 1043 | (522) | 944 | (555) | 811 | (694) |

*Note*. Accuracies are given in proportion of correct responses. Response latencies are given in milliseconds. Standard deviations are presented in brackets.
Group 1: Unmarked order dimension; Group 2: Marked order dimension

Table 4  Experiment 5, Accuracies and Response latencies by Display direction for dominant person, and Pair distance.

| Group 1 | Dominant person | Pair distance 1 step | | 2 step | | 3 steps | | 4 steps | |
|---|---|---|---|---|---|---|---|---|---|
| Accuracy | top | .761 | (.074) | .839 | (.086) | .892 | (.057) | .899 | (.094) |
| | bottom | .718 | (.142) | .820 | (.103) | .866 | (.108) | .912 | (.098) |
| Latency | top | 1091 | (329) | 1038 | (322) | 891 | (294) | 777 | (399) |
| | bottom | 1116 | (303) | 1037 | (307) | 982 | (298) | 903 | (369) |
| **Group 2** | | | | | | | | | |
| Accuracy | top | .805 | (.085) | .874 | (.099) | .916 | (.093) | .946 | (.077) |
| | bottom | .787 | (.106) | .869 | (.103) | .933 | (.085) | .960 | (.098) |
| Latency | top | 1421 | (493) | 1287 | (464) | 1161 | (480) | 1030 | (562) |
| | bottom | 1432 | (480) | 1369 | (490) | 1233 | (504) | 1197 | (658) |

*Note*. Accuracies are given in proportion of correct responses. Response latencies are given in milliseconds. Standard deviations are presented in brackets.
Group 1: Dominant responding; Group 2: Non-dominant responding.

Table 5 Experiment 6, Accuracies and Response latencies by Display direction for dominant person, and Pair distance.

| Group 1 | Dominant person | Pair distance 1 step | | 2 step | | 3 steps | | 4 steps | |
|---|---|---|---|---|---|---|---|---|---|
| Accuracy | top | .773 | (.089) | .858 | (.099) | .916 | (.069) | .916 | (.138) |
| | bottom | .736 | (.088) | .824 | (.126) | .837 | (.153) | .916 | (.161) |
| Latency | top | 1007 | (319) | 918 | (260) | 851 | (168) | 826 | (213) |
| | bottom | 1031 | (316) | 994 | (258) | 908 | (245) | 798 | (110) |

| Group 2 | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Accuracy | top | .739 | (.088) | .829 | (.108) | .874 | (.109) | .906 | (.093) |
| | bottom | .705 | (.122) | .822 | (.091) | .864 | (.085) | .906 | (.082) |
| Latency | top | 1292 | (397) | 1161 | (366) | 1075 | (327) | 959 | (383) |
| | bottom | 1334 | (429) | 1288 | (400) | 1158 | (356) | 1075 | (313) |

*Note*. Accuracies are given in proportion of correct responses. Response latencies are given in milliseconds. Standard deviations are presented in brackets.
Group 1: Purple jumpers; Group 2: Green jumpers.

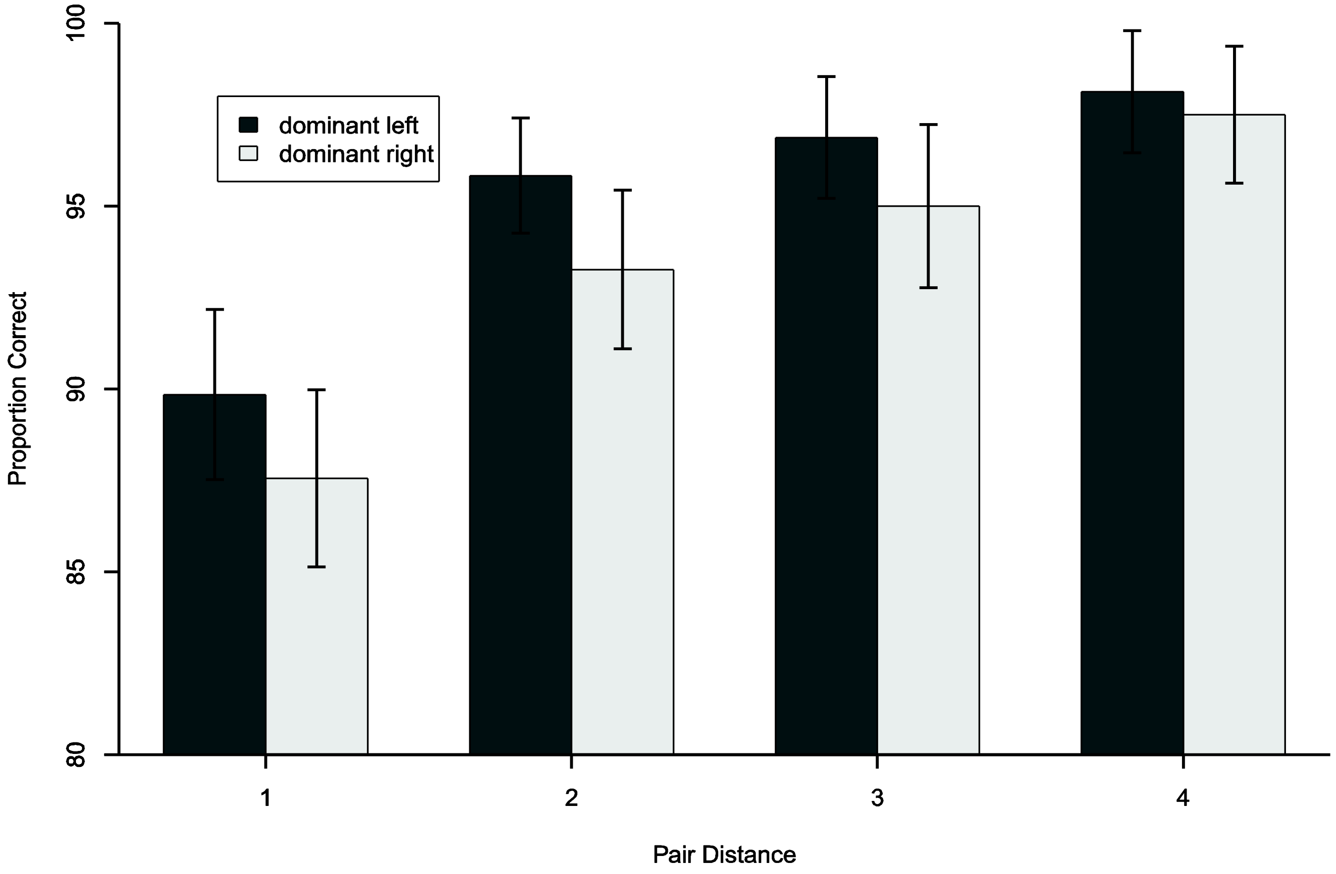
Table 6 Experiment 7a and 7b, Accuracies and Response latencies by Display direction for dominant person, and Pair distance, in both samples.

| | | Pair distance | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 7a) *Farsi-English sample* | Dominant person | 1 step | | 2 step | | 3 steps | | 4 steps | |
| Accuracy | left | .628 | (.163) | .663 | (.162) | .712 | (.150) | .733 | (.159) |
| | right | .629 | (.178) | .690 | (.170) | .708 | (.181) | .733 | (.194) |
| Latency | left | 2054 | (871) | 1992 | (972) | 1807 | (894) | 1705 | (1199) |
| | right | 2083 | (992) | 2017 | (983) | 1993 | (1164) | 1739 | (1033) |
| 7b) *Farsi sample* | | | | | | | | | |
| Accuracy | left | .490 | (.096) | .534 | (.089) | .567 | (.104) | .607 | (.140) |
| | right | .552 | (.092) | .607 | (.117) | .574 | (.103) | .621 | (.134) |
| Latency | left | 2262 | (1293) | 2291 | (1506) | 2146 | (1376) | 1958 | (1378) |
| | right | 2202 | (1362) | 2099 | (1317) | 1896 | (1174) | 1965 | (1352) |

*Note*. Accuracies are given in proportion of correct responses. Response latencies are given in milliseconds. Standard deviations are presented in brackets.

List of Figures

Figure 1



100
95
90
85
80
Proportion Correct
dominant left
dominant right
1
2
3
4
Pair Distance

Figure 2

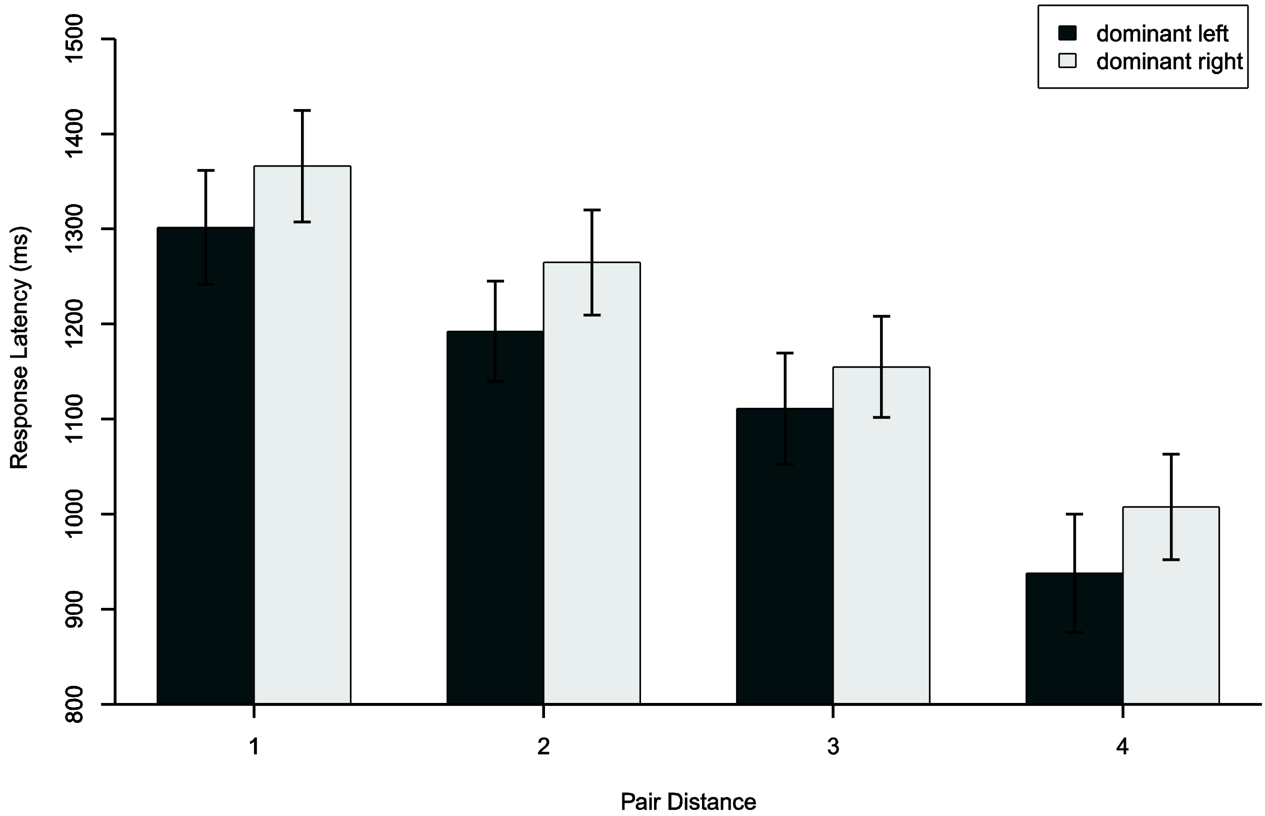
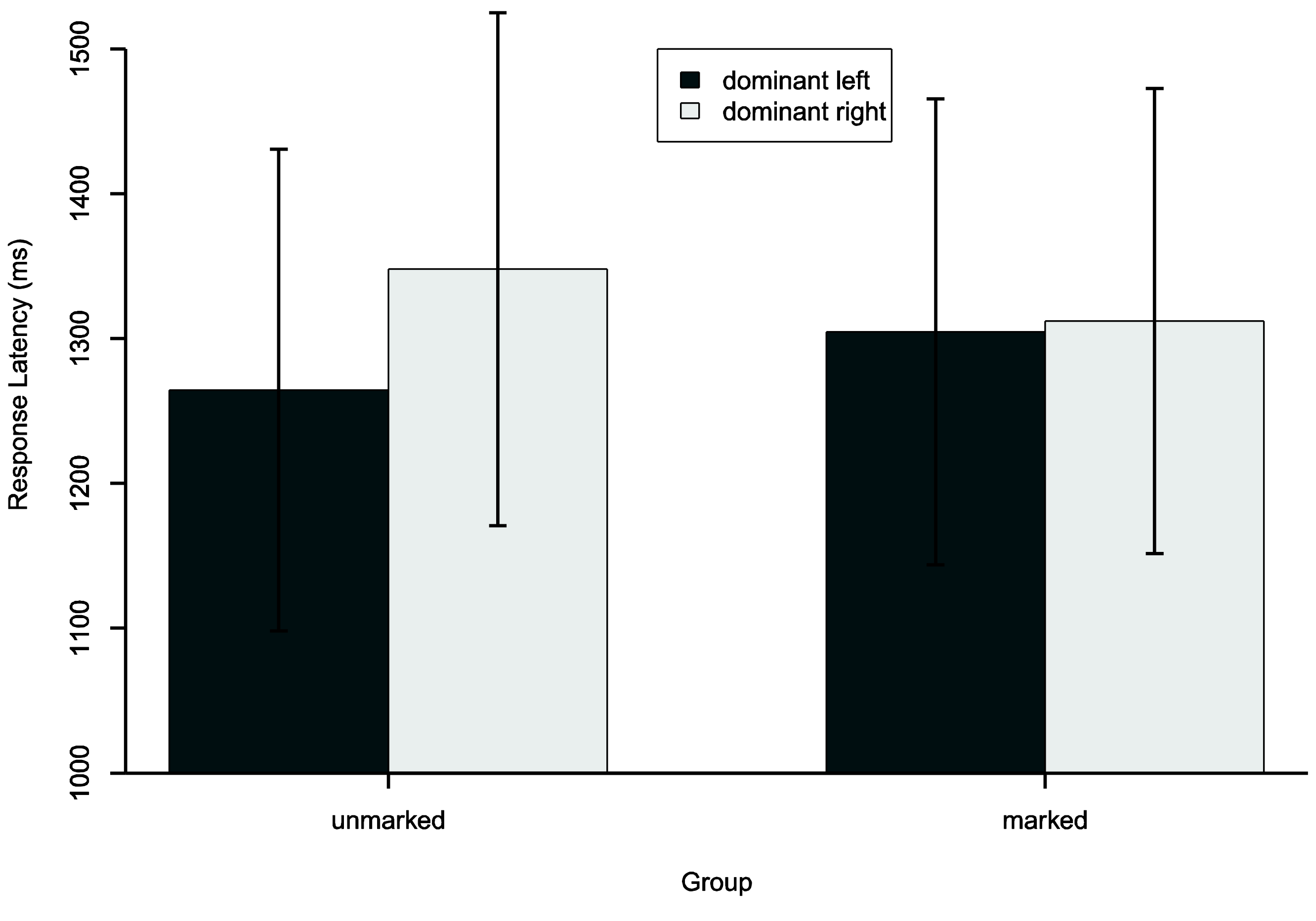
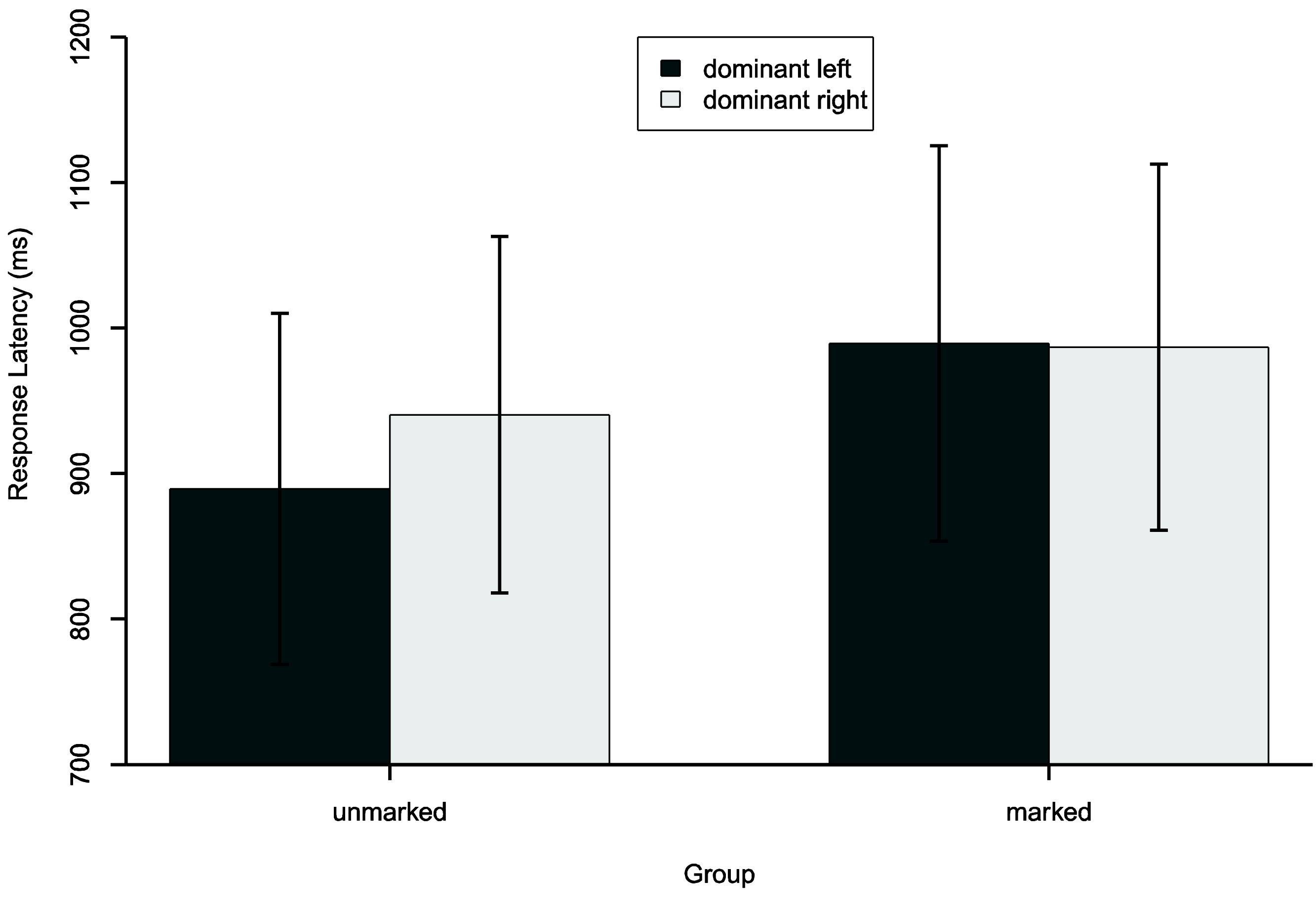

dominant left
dominant right
Response Latency (ms)
800
900
1000
1100
1200
1300
1400
1500
1
2
3
4
Pair Distance

Figure 3



1500
1400
1300
1200
1100
1000
Response Latency (ms)
dominant left
dominant right
unmarked
marked
Group

Figure 4



dominant left
dominant right
Response Latency (ms)
1200
1100
1000
900
800
700
unmarked
marked
Group

**Appendix A:**

Name sets as used in the English-spoken experiments

(1)Peter, Ray, Andrew, Tom, Luke;

(2) Keith, Frank, Robert, Matthew, Steve;

(3) Ben, Neil, Timothy, John, Craig;

(4) Katie, Louise, Emma, Bridgit, Penny;

(5) Tanya, Karen, Anna, Denise, Zoe;

(6) Sue, Kimberly, Sarah, Laura, Rhian.

## Appendix B: Modelling of effects

In order to determine which random effect structure to assume, we used generalized linear mixed models with random effects for *participants* for accuracy data, and linear mixed models with random effects for *participants* for the latency data.

Model comparisons were performed in a two-steps procedure: In the first step, we fitted four models for each data type (a1, a2, a3, a4 for accuracy data, and tm1, tm2, tm3, and tm4 for latency data). All of these models had the same fixed effect structure, that is, group (if applicable), presentation side of the dominant element (dom_side), pair distance (dist), and type of relation (rel), as well as their interactions. The standardised average ordinal position of the pair on the hypothetical dimension was entered as a predictor (z_pos), as was the interaction z_pos x dom_side. All models had a random intercept for participants (1 | part). Models a4 and tm4 had only this intercept, so these models are minimal. Models a1 / tm1 also had a random slope for dom_side as function of participant, whereas a2 / tm2 had a random slope for relation instead, and a3 / tm3 had a random slope for pair distance instead. These models were then compared using the Chi square difference statistic $\Delta\chi^2$. Models of a given type 1..3 were compared with the corresponding model of type 4, the minimal model. If there was a significant difference in fit, the particular type of random slope as specified in the non-minimal model under comparison was then retained for the final model, afinal, resp., tfinal. In a second step, these final models were assembled and run in order to evaluate the respective fixed effect structure from those models (see Jaeger, 2008). This stragegy thus considers random intercepts and random slopes for the main effects of the experimental design. Models with more complex random effects structures (e.g., random slopes for interactions) could not be estimated in reasonable amounts of time. The analyses employed the statistical programming language R (R Core Team, 2014), using the package lme4 (Bates, Maechler, Bolker, & Walker, 2015) and afex (Singmann, 2014).

**Experiment 1**

*Accuracies*

| Model | *df* | *AIC* | *BIC* | *loglik* | *deviance* | $\Delta\chi^2$ | $\Delta df$ | *p* |
|---|---|---|---|---|---|---|---|---|
| a4 | 99 | 4421.1 | 5130.9 | -2111.6 | 4223.1 | | | |
| a1 | 101 | 4424.4 | 5148.5 | -2111.2 | 4222.4 | 0.7188 | 2 | 0.6981 |
| a2 | 119 | 4240.5 | 5093.6 | -2001.2 | 4002.5 | 220.68 | 20 | 2.2e-16 |
| a3 | 108 | 4430.6 | 5204.9 | -2107.3 | 4214.6 | 8.5854 | 9 | 0.4764 |

afinal = a2, i.e., random slopes for type of relation as a function of participants are kept.

*Latencies*

| Model | *df* | *AIC* | *BIC* | *loglik* | *deviance* | $\Delta\chi^2$ | $\Delta df$ | *p* |
|---|---|---|---|---|---|---|---|---|
| t4 | 100 | 129658 | 130363 | -64729 | 129458 | | | |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| t1 | 102 | 129659 | 130379 | -64728 | 129455 | 2.2429 | 2 | 0.3258 |
| t2 | 120 | 129412 | 130259 | -64586 | 129172 | 285.47 | 2 | 2.2e-16 |
| t3 | 109 | 129591 | 130360 | -64686 | 129373 | 84.742 | 9 | 1.837e-14 |

tfinal = random slopes for type of relation and pair distance, as a function of participants, are kept.

**Experiment 2**

*Accuracies*

| Model | *df* | *AIC* | *BIC* | *loglik* | *deviance* | $\Delta\chi^2$ | $\Delta df$ | *p* |
|---|---|---|---|---|---|---|---|---|
| a4 | 147 | 10019 | 11130 | -4862.5 | 9725.1 | | | |
| a1 | 149 | 10011 | 11137 | -4856.3 | 9712.6 | 12.483 | 2 | 0.001947 |
| a2 | 167 | 9521 | 10783 | -4593.5 | 9187.0 | 538.08 | 20 | 2.2e-16 |
| a3 | 156 | 9986 | 11165 | -4837.0 | 9674.0 | 51.095 | 9 | 6.699e-08 |

afinal = random slopes for side of dominant element, type of relation, and pair distance, as a function of participants, are kept.

*Latencies*

| Model | *df* | *AIC* | *BIC* | *loglik* | *deviance* | $\Delta\chi^2$ | $\Delta df$ | *p* |
|---|---|---|---|---|---|---|---|---|
| t4 | 148 | 178970 | 180059 | -89337 | 178674 | | | |
| t1 | 150 | 178965 | 180069 | -89333 | 178665 | 8.8442 | 2 | 0.01201 |
| t2 | 168 | 178062 | 179298 | -88863 | 177726 | 947.96 | 20 | 2.2e-16 |
| t3 | 157 | 178966 | 180121 | -89326 | 178652 | 22.255 | 9 | 0.008105 |

tfinal = random slopes for side of dominant element, type of relation, and pair distance, as a function of participants, are kept.

**Experiment 3**

*Accuracies*

| Model | *df* | *AIC* | *BIC* | *loglik* | *deviance* | $\Delta\chi^2$ | $\Delta df$ | *p* |
|---|---|---|---|---|---|---|---|---|

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| a4 | 101 | 6617.2 | 7338.7 | -3207.6 | 6415.2 | | | |
| a1 | 103 | 6619.8 | 7355.7 | -3206.9 | 6413.8 | 1.344 | 2 | 0.5105 |
| a2 | 121 | 6260.4 | 7124.8 | -3009.2 | 6018.4 | 396.76 | 20 | 2.2e-16 |
| a3 | 110 | 6592.8 | 7378.6 | -3186.4 | 6372.8 | 42.388 | 9 | 2.791e-06 |

afinal = random slopes for type of relation and pair distance, as a function of participants, are kept.

*Latencies*

| Model | *df* | *AIC* | *BIC* | *loglik* | *deviance* | $\Delta\chi^2$ | $\Delta df$ | *p* |
|---|---|---|---|---|---|---|---|---|
| t4 | 100 | 118919 | 119615 | -59360 | 118719 | | | |
| t1 | 102 | 118913 | 119622 | -59354 | 118709 | 10.437 | 2 | 0.0541 |
| t2 | 120 | 118512 | 119347 | -59136 | 118272 | 447.09 | 20 | 2.2e-16 |
| t3 | 109 | 118924 | 119683 | -59353 | 118706 | 12.913 | 9 | 0.1666 |

tfinal = random slopes for side of dominant element and type of relation, as a function of participants, are kept.

**Experiment 4a**

*Accuracies*

| Model | *df* | *AIC* | *BIC* | *loglik* | *deviance* | $\Delta\chi^2$ | $\Delta df$ | *p* |
|---|---|---|---|---|---|---|---|---|
| a4 | 101 | 7027.0 | 7758.4 | -3412.5 | 6825.0 | | | |
| a1 | 103 | 7028.8 | 7774.8 | -3411.4 | 6822.8 | 2.1114 | 2 | 0.348 |
| a2 | 121 | 6495.0 | 7371.3 | -3126.5 | 6253 | 571.95 | 20 | 2.2e-16 |
| a3 | 110 | 7006.5 | 7803.1 | -3393.2 | 6786.5 | 38.468 | 9 | 1.437e-05 |

afinal = random slopes for type of relation and pair distance, as a function of participants, are kept.

*Latencies*

| Model | *df* | *AIC* | *BIC* | *loglik* | *deviance* | $\Delta\chi^2$ | $\Delta df$ | *p* |
|---|---|---|---|---|---|---|---|---|
| t4 | 100 | 140015 | 140721 | -69907 | 139815 | | | |
| t1 | 102 | 140014 | 140734 | -69905 | 139810 | 4.9689 | 2 | 0.08337 |
| t2 | 120 | 139255 | 140103 | -69508 | 139015 | 799.71 | 20 | 2.2e-16 |
| t3 | 109 | 139978 | 140748 | -69880 | 139760 | 54.429 | 9 | 1.565e-08 |

tfinal = random slopes for type of relation and pair distance, as a function of participants, are kept.

**Experiment 4b**

*Accuracies*

| Model | *df* | *AIC* | *BIC* | *loglik* | *deviance* | $\Delta\chi^2$ | $\Delta df$ | *p* |
|---|---|---|---|---|---|---|---|---|
| a4 | 101 | 8892.1 | 9634.6 | -4345.1 | 8690.1 | | | |
| a1 | 103 | 8888.2 | 9645.5 | -4341.1 | 8682.2 | 7.8886 | 2 | 0.01936 |
| a2 | 121 | 8274.6 | 9164.2 | -4016.3 | 8032.6 | 657.52 | 20 | 2.2e-16 |
| a3 | 110 | 8848.8 | 9657.5 | -4314.4 | 8628.8 | 61.332 | 9 | 7.417e-10 |

afinal = random slopes for side of dominant element, type of relation and pair distance, as a function of participants, are kept.

*Latencies*

| Model | *df* | *AIC* | *BIC* | *loglik* | *deviance* | $\Delta\chi^2$ | $\Delta df$ | *p* |
|---|---|---|---|---|---|---|---|---|
| t4 | 100 | 145839 | 146552 | -72820 | 145639 | | | |
| t1 | 102 | 145843 | 146570 | -72819 | 145639 | 0.5588 | 2 | 0.7562 |
| t2 | 120 | 144879 | 145734 | -72319 | 144639 | 1000.5 | 20 | 2.2e-16 |
| t3 | 109 | 145775 | 146552 | -72779 | 145557 | 82.054 | 9 | 6.31e-14 |

tfinal = random slopes for type of relation and pair distance, as a function of participants, are kept.

**Experiment 5**

*Accuracies*

| Model | *df* | *AIC* | *BIC* | *loglik* | *deviance* | $\Delta\chi^2$ | $\Delta df$ | *p* |
|---|---|---|---|---|---|---|---|---|
| a4 | 101 | 5778.2 | 6491.6 | -2788.1 | 5576.2 | | | |
| a1 | 103 | 5776.9 | 6504.5 | -2785.5 | 5570.9 | 5.242 | 2 | 0.07273 |
| a2 | 121 | 5382.2 | 6236.9 | -2570.1 | 5140.2 | 436 | 20 | 2.2e-16 |
| a3 | 110 | 5771.9 | 6548.9 | -2775.9 | 5551.9 | 24.285 | 9 | 0.003872 |

afinal = random slopes for location of dominant element, type of relation and pair distance, as a function of participants, are kept.

*Latencies*

| Model | *df* | *AIC* | *BIC* | *loglik* | *deviance* | $\Delta\chi^2$ | $\Delta df$ | *p* |
|---|---|---|---|---|---|---|---|---|
| t4 | 100 | 110911 | 111600 | -55356 | 110711 | | | |
| t1 | 102 | 110908 | 111611 | -55352 | 110704 | 6.914 | 2 | 0.03152 |
| t2 | 120 | 110639 | 111465 | -55199 | 110399 | 312.43 | 20 | 2.2e-16 |
| t3 | 109 | 110920 | 111670 | -55351 | 110702 | 9.5171 | 9 | 0.391 |

tfinal = random slopes for type of relation and location of dominant element, as a function of participants, are kept.

**Experiment 6**

*Accuracies*

| Model | *df* | *AIC* | *BIC* | *loglik* | *deviance* | $\Delta\chi^2$ | $\Delta df$ | *p* |
|---|---|---|---|---|---|---|---|---|
| a4 | 21 | 2985.4 | 3118.0 | -1471.7 | 2943.4 | | | |
| a1 | 23 | 2988.9 | 3134.2 | -1471.5 | 2942.9 | 0.4548 | 2 | 0.7966 |
| a3 | 30 | 2990.0 | 3179.4 | -1465.0 | 2930.0 | 13.442 | 9 | 0.1436 |

afinal = no random slopes, as a function of participants, are kept.

*Latencies*

| Model | *df* | *AIC* | *BIC* | *loglik* | *deviance* | $\Delta\chi^2$ | $\Delta df$ | *p* |
|---|---|---|---|---|---|---|---|---|
| t4 | 20 | 50327 | 50449 | -25143 | 50287 | | | |
| t1 | 22 | 50330 | 50464 | -25143 | 50286 | 0.9348 | 2 | 0.6266 |
| t3 | 29 | 50319 | 50496 | -25130 | 50261 | 26.105 | 9 | 0.001964 |

tfinal = random slopes for pair distance, as a function of participants, are kept.

NB: Models a2 and t2 were not applicable in this experiment because only one relation was used (see text).

**Experiment 7a**

*Accuracies*

| Model | *df* | *AIC* | *BIC* | *loglik* | *deviance* | $\Delta\chi^2$ | $\Delta df$ | *p* |
|---|---|---|---|---|---|---|---|---|
| a4 | 51 | 5464.9 | 5795.2 | -2681.4 | 5362.9 | | | |
| a1 | 53 | 4984.3 | 5327.5 | -2439.1 | 4878.3 | 484.64 | 2 | 2.2e-16 |
| a2 | 71 | 4341.8 | 4801.6 | -2099.9 | 4199.8 | 1163.1 | 20 | 2.2e-16 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| a3 | 60 | 5480.7 | 5869.3 | -2680.4 | 5360.7 | 2.1765 | 9 | 0.9884 |

afinal = random slopes for location of dominant element and type of relation, as a function of participants, are kept.

Latencies

| Model | *df* | *AIC* | *BIC* | *loglik* | *deviance* | $\Delta\chi^2$ | $\Delta df$ | *p* |
|---|---|---|---|---|---|---|---|---|
| t4 | 52 | 52874 | 53188 | -26385 | 52770 | | | |
| t1 | 54 | 52874 | 53201 | -26383 | 52766 | 3.236 | 2 | 0.1983 |
| t2 | 72 | 52760 | 53195 | -26308 | 52616 | 153.73 | 20 | 2.2e-16 |
| t3 | 61 | 52884 | 53253 | -26381 | 52762 | 7.9458 | 9 | 0.5396 |

tfinal = random slopes for type of relation, as a function of participants, are kept.

**Experiment 7b**

*Accuracies*

| Model | *df* | *AIC* | *BIC* | *loglik* | *deviance* | $\Delta\chi^2$ | $\Delta df$ | *p* |
|---|---|---|---|---|---|---|---|---|
| a4 | 11 | 7545.0 | 7618.3 | -3761.5 | 7523.0 | | | |
| a1 | 13 | 7546.8 | 7633.4 | -3760.4 | 7520.8 | 2.1907 | 2 | 0.3344 |
| a2 | 13 | 7333.0 | 7419.6 | -3653.5 | 7307 | 216 | 2 | 2.2e-16 |
| a3 | 20 | 7561.6 | 7694.7 | -3760.8 | 7521.6 | 1.4762 | 9 | 0.9973 |

afinal = random slopes for type of relation, as a function of participants, are kept.

Latencies

| Model | *df* | *AIC* | *BIC* | *loglik* | *deviance* | $\Delta\chi^2$ | $\Delta df$ | *p* |
|---|---|---|---|---|---|---|---|---|
| t4 | 12 | 56358 | 56431 | -28167 | 56334 | | | |
| t1 | 14 | 56362 | 56447 | -28167 | 56334 | 0.0212 | 2 | 0.9894 |
| t2 | 14 | 55942 | 56027 | -27957 | 55914 | 419.89 | 2 | 2.2e-16 |
| t3 | 21 | 56355 | 56483 | -28156 | 56313 | 21.06 | 9 | 0.01239 |

tfinal = random slopes for type of relation, as a function of participants, are kept.